Preliminary Root Causes Analysis of Failures of the Oroville Dam Gated Spillway

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This Preliminary Root Cause Analysis of the failures of the Oroville Dam gated spillways is based on current publically available photographic and written documentation included and cited at the end of this document.

Design Defects and Flaws

The origins of the gated spillway failures are deeply rooted in pervasive design defects and flaws developed by the California Department of Water Resources (DWR). These design defects and flaws included the following:

1. Spillway base slabs of insufficient thickness for the design hydraulic conditions: 4 to 6 inches thick at minimum points;
2. Spillway base slabs not joined with 'continuous' steel reinforcement to prevent lateral and vertical separations;
3. Spillway base slabs designed without effective water stop barriers embedded in both sides of joints to prevent water intrusion under the base slabs;
4. Spillway base slabs not designed with two layers of continuous steel reinforcement (top and bottom) to provide sufficient flexural strength required for operating conditions; and
5. Spillway base slabs designed with ineffective ‘ground’ anchors to prevent significant lateral and vertical movements.

Construction Defects and Flaws

The design defects and flaws were propagated by DWR during construction of the spillway. These construction defects and flaws included the following:

1. Failure to excavate the native soils and incompetent rock overlying the competent rock foundation assumed as a basic condition during the spillway design phase, and fill the voids with concrete, and
2. Failure to prevent spreading gravel used as part of the under-slab drainage systems and ‘native’ soils to form extensive 'blankets' of permeable materials in which water could collect and erode.

Maintenance Defects and Flaws

The design and construction defects and flaws were propagated by DWR during maintenance of the spillway. These maintenance defects and flaws included the following:

1. Repeated ineffective repairs made to cracks and joint displacements to prevent water stagnation and cavitation pressure intrusion under the base slabs with subsequent erosion of the spillway subgrade; and
2. Allowing large trees to grow adjacent to the spillway walls whose roots could intrude below the base slabs and into the subgrade drainage pipes resulting in reduced flow and plugging of the drainage pipes.

February 2017 spillway releases

By the time of the February 2017 spillway releases, the gated spillway had become heavily undermined and the subgrade eroded by previous flood releases. The first spillway release completed the undermining of the spillway slabs, allowing water cavitation and stagnation pressures to lift the 'weak' slabs and break them into pieces (U.S. Department of the Interior Bureau of Land Management and U.S. Army Corps of Engineers, 2015; United States Department of the Interior Bureau of Reclamation, 2007).

After the almost catastrophic water release over the un-surfaced Auxiliary Spillway, the subsequent water releases down the gated spillway propagated the initial spillway breach until spillway releases ceased.

Root Causes Analysis

Currently available information indicates the Root Causes of the gated spillway failures are founded primarily in 'Extrinsic' uncertainties (human and organizational task performance and knowledge development and utilization) developed and propagated by DWR during the gated spillway design, construction, and maintenance activities (Bea, 2016).

A key question that can not be answered at this time is: "why did DWR and the responsible State and Federal regulatory agencies (California Water Commission, Federal Energy Regulatory Commission) allow these Root Causes to develop and persist during the almost 50 year life of the gated spillway?"

One answer that has been offered is that the spillway was designed and constructed according to the 'Standards of the time." While that answer may or may not be factual or true, current evidence indicates the original spillway design and construction does not meet current guidelines and standards.

Another answer that has been offered is that the spillway operated for almost 50 years and was subjected to water discharges that exceeded those developed during 2017 without failure. Recent inspections indicated that the spillway was in 'satisfactory condition.' The conclusion prior to the February 2017 discharges was the gated spillway consequently was 'suitable for service.' The experience prior to the DWR attempt on February 11 to use the Emergency Spillway indicated that conclusion was not valid. The gated spillway failed during discharges that were much less than the design conditions.

The author's previous experiences with investigations of failures of public infrastructure systems (e.g. New Orleans hurricane flood protection system during Hurricanes Katrina and Rita) leads

to a conclusion that it is likely that the wrong standards and guidelines are being used to re-qualify many critical infrastructure systems for continued service. The majority of these standards and guidelines were originally intended for design, not re-qualification or re-assessment of existing aged infrastructure systems that have experienced 'aging,' 'technological obsolesce,' and increased risk (likelihoods and consequences of major failures) effects. Inappropriate standards and guidelines are being used to re-qualify these infrastructure systems for continued service. The currently available information indicates this is one of the primary Root Causes of the failures of the Orville Dam gated spillway.

References

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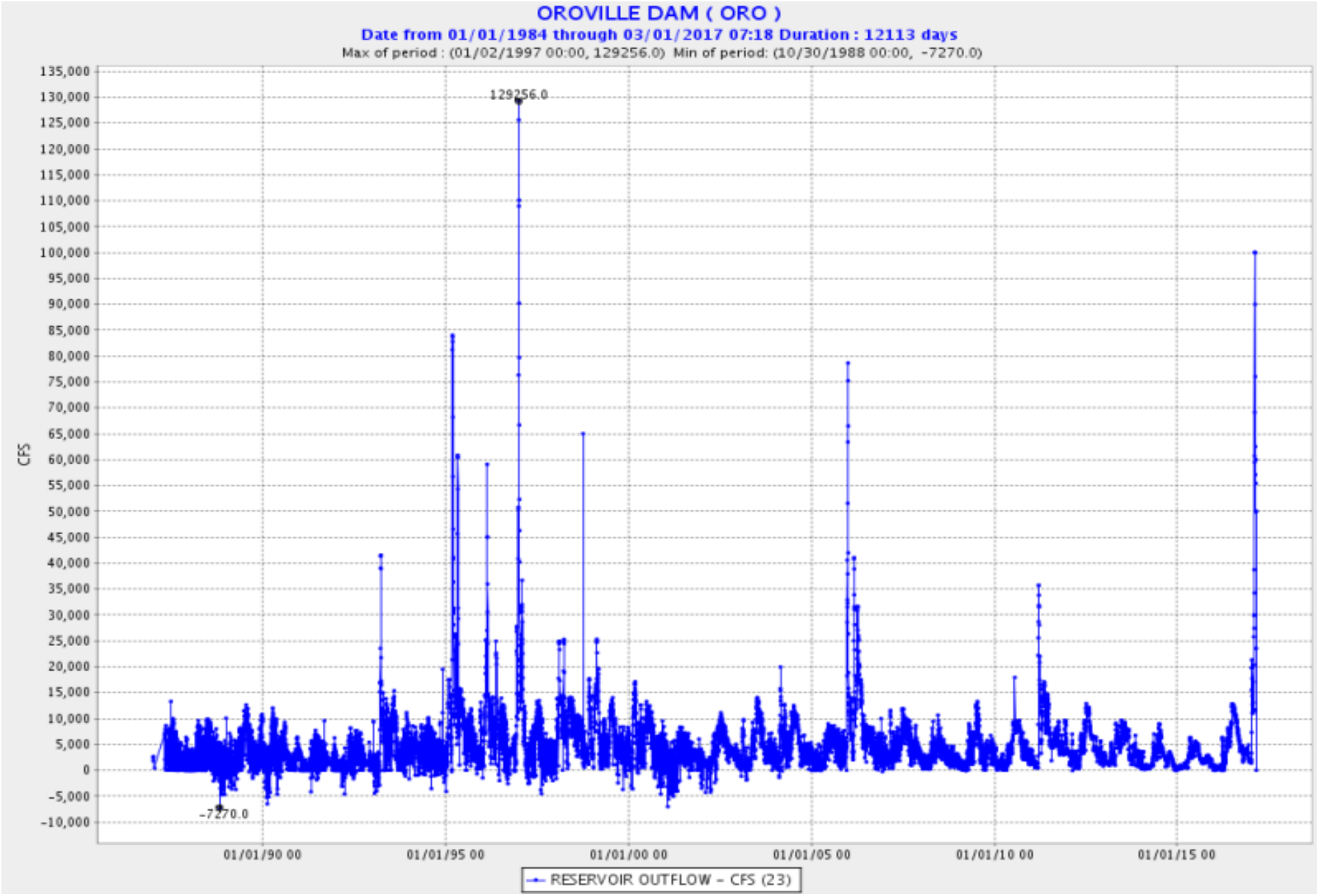
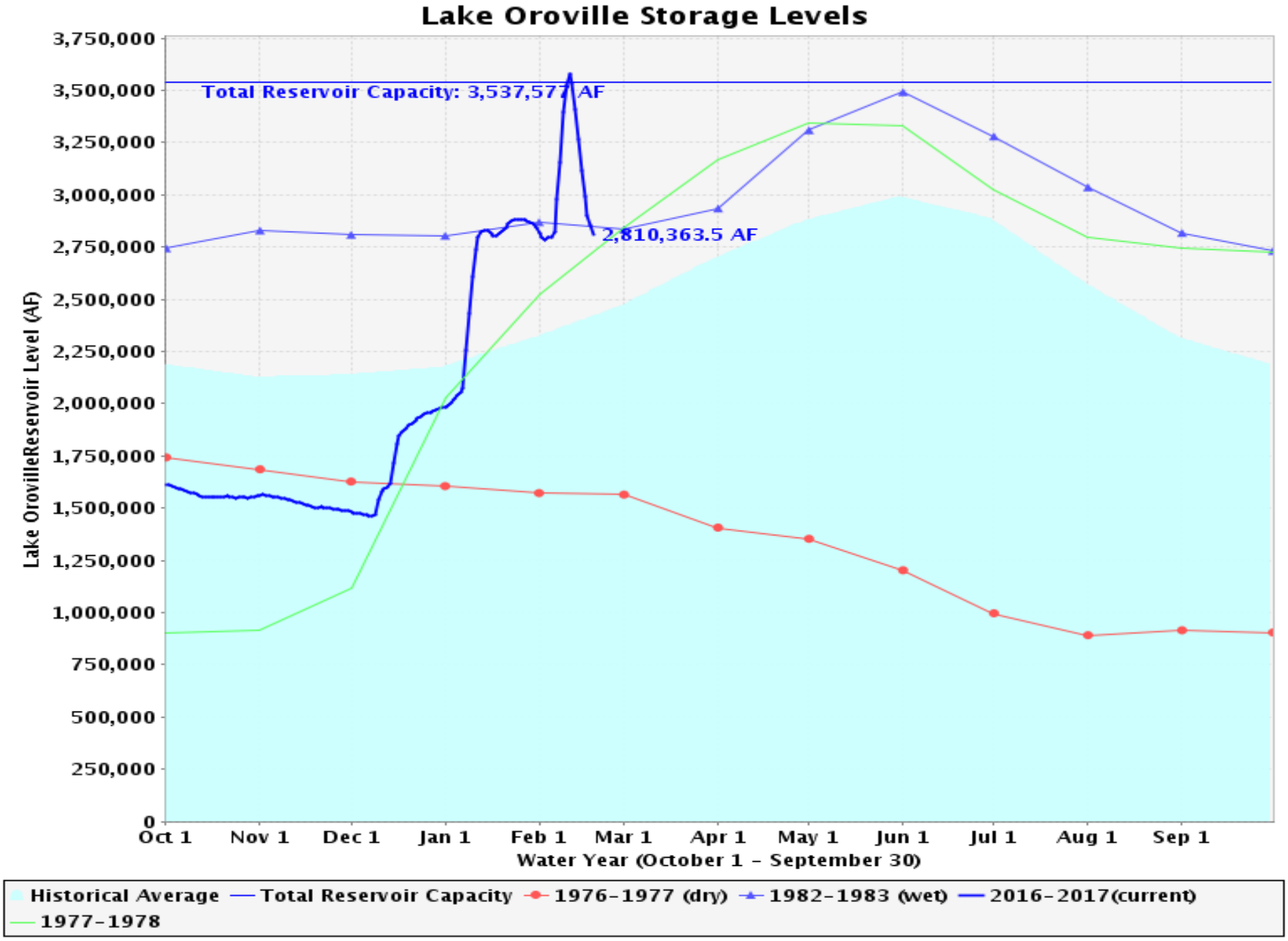
Spillway Discharges




Lake Oroville Storage Levels
Total Reservoir Capacity: 3,537,577 AF
2,810,363.5 AF
Lake OrovilleReservoir Level (AF)
3,750,000
3,500,000
3,250,000
3,000,000
2,750,000
2,500,000
2,250,000
2,000,000
1,750,000
1,500,000
1,250,000
1,000,000
750,000
500,000
250,000
0
Oct 1
Nov 1
Dec 1
Jan 1
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Water Year (October 1 – September 30)
Historical Average
Total Reservoir Capacity
1976–1977 (dry)
1982–1983 (wet)
2016–2017(current)
1977–1978

Lake Oroville Spillway Incident: Timeline of Major Events February 4-25

Oroville Spillway Public Info Line: (530) 538-7826

❶ **February 7:** As water releases from the flood control spillway ramp up to 54,500 cubic feet per second (cfs), in anticipation of inflows expected from rainfall, DWR employees notice an unusual flow pattern. Spillway flows stop for investigation. Engineers find large area of concrete erosion.

❷ **February 8:** DWR begins ongoing consultation with FERC and other dam safety agencies. DWR runs test flows down the damaged spillway, monitoring further erosion, and prepares for possible use of emergency spillway. 24/7 emergency interagency operations centers activate to study and implement response to flood control spillway and related structures, with careful study of weather forecasts.

❸ **February 11:** Inflow to Lake Oroville brings lake level above 901 feet. This engages the emergency spillway for the first time in the history of the facility.

❹ **February 12:** Anticipated erosion begins to progress faster than expected at the base of the emergency spillway. The Butte County Sheriff's Office issues mandatory evacuation orders for the Oroville area. To ease pressure on the emergency spillway, the flood control spillway outflow is increased to 100,000 cfs. After several hours, inflows decrease and overflow stops at the emergency spillway. Erosion to the emergency spillway hillside is assessed.

❺ **February 13:** DWR crews begin working around the clock to repair the emergency spillway. Evacuation orders remain in effect.

❻ **February 14:** As the lake level continues to drop, the mandatory evacuation order is modified to an evacuation warning. Crews continue working around the clock to repair the emergency spillway. An elevation of 850' is targeted for lake level.

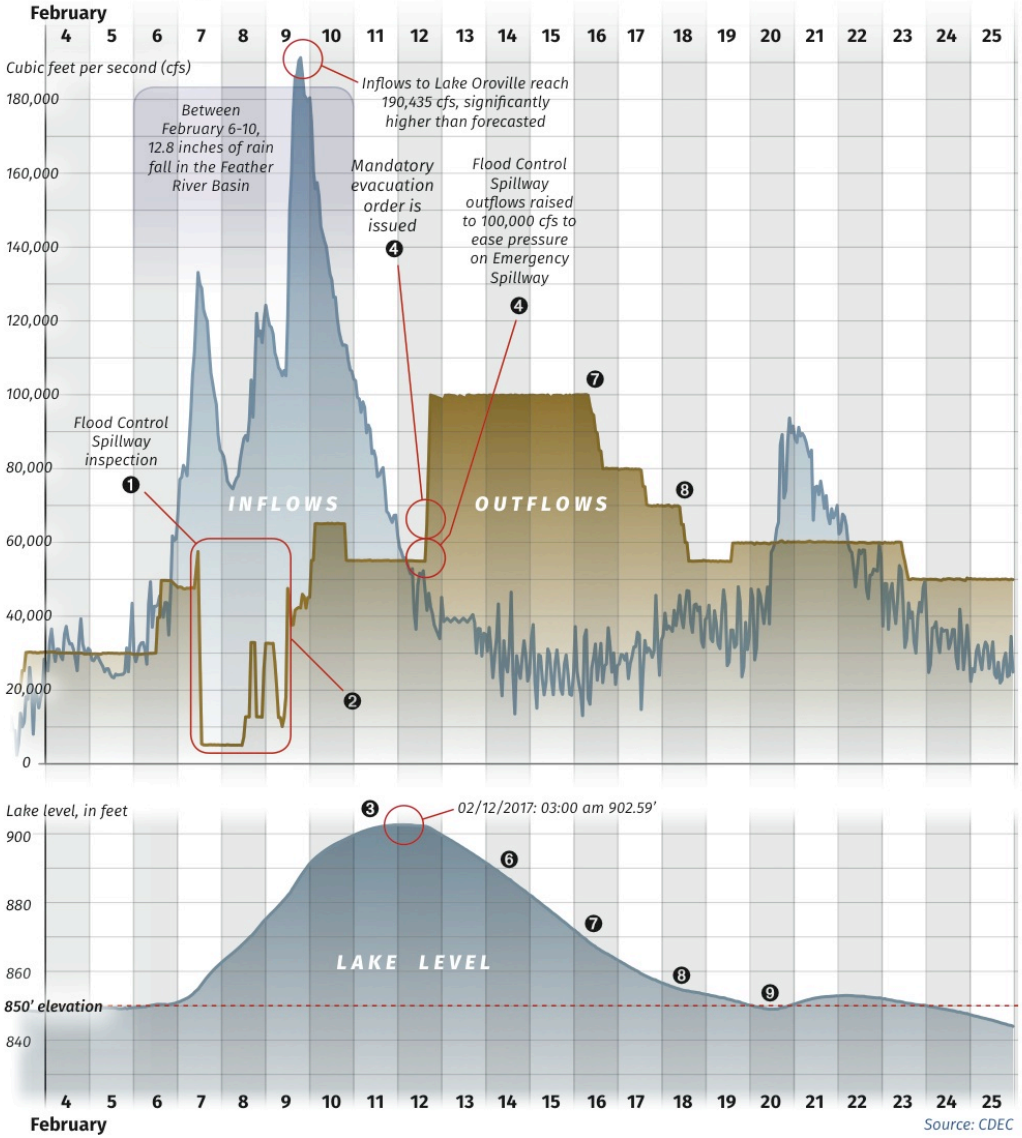
❼ **February 16:** Flood control spillway flows are reduced below 100,000 cfs to facilitate the clearing of debris from below the spillway. Lake levels continue to drop. Construction to armor the emergency spillway continues.

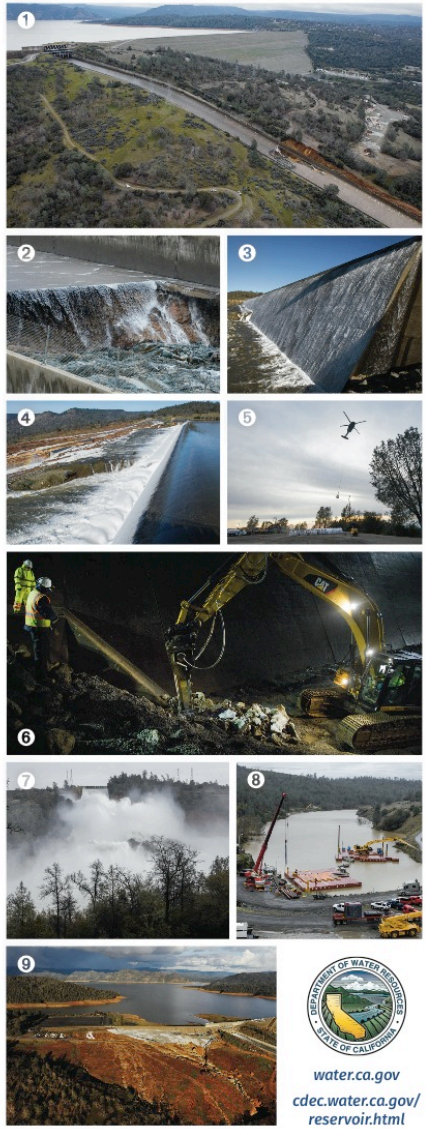
❽ **February 18:** Lake level down to 854 feet. Flood control spillway flows are reduced to 55,000 cfs. Barge construction begins in order to remove debris from the diversion pool beneath the spillway.

❾ **February 20:** Lake Oroville elevation reaches 848.95 feet at 11 a.m. Repairs and preparations continue around the clock.

Cooperating Agencies: California Department of Water Resources, Butte County Sheriff, CAL FIRE, Oroville Police Department, Butte County OES, Oroville Fire Department, Butte County Public Works, Oroville Hospital, Caltrans, California Highway Patrol, California State Parks, California Conservation Corps, California National Guard, California Department of Fish and Wildlife, PG&E, Red Cross, Bureau of Indian Affairs, CAL OES, USACE, FERC, FEMA

For more imagery, see DWR Pixel Library

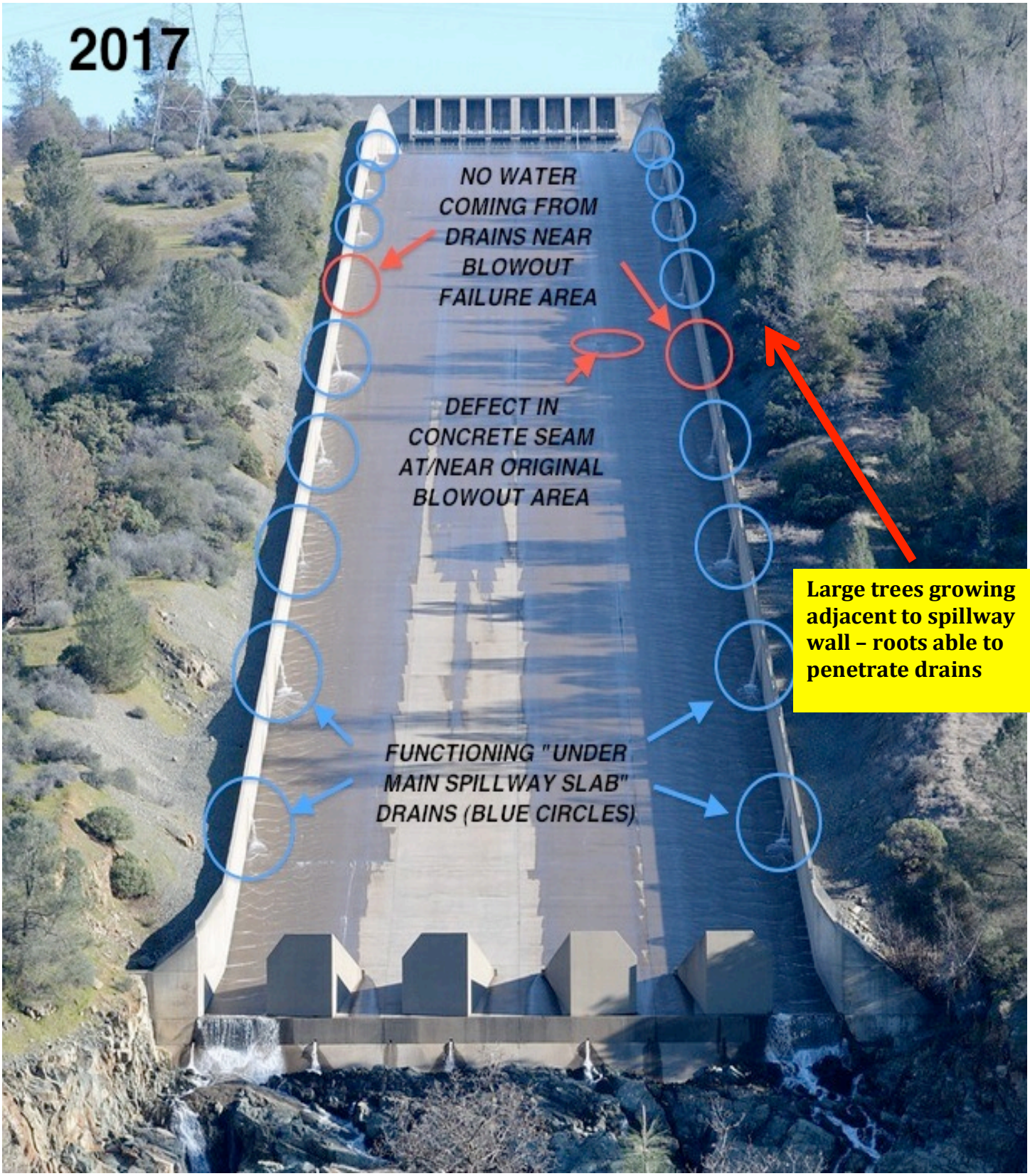




water.ca.gov

cdec.water.ca.gov/reservoir.html

January 27, 2017

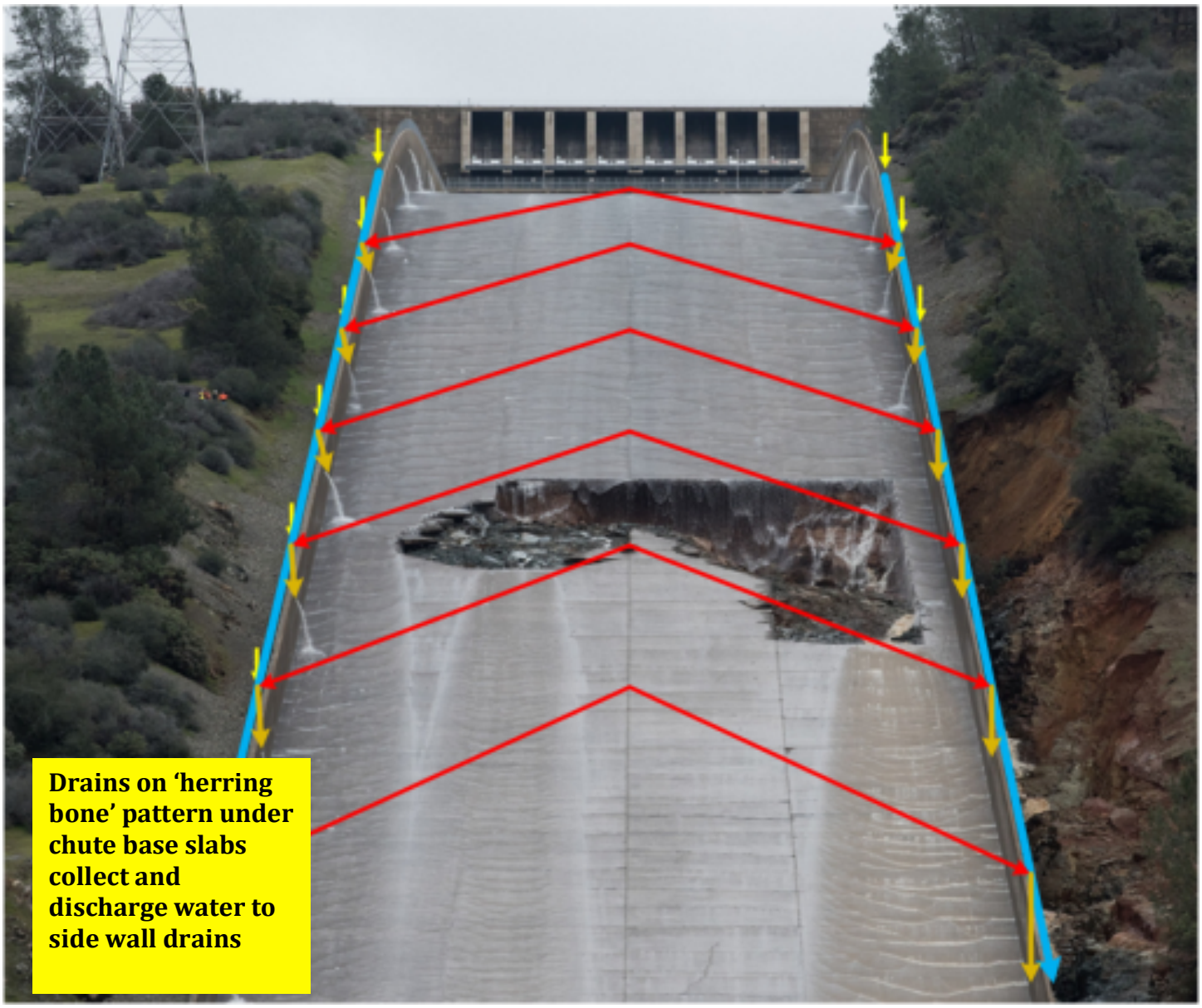


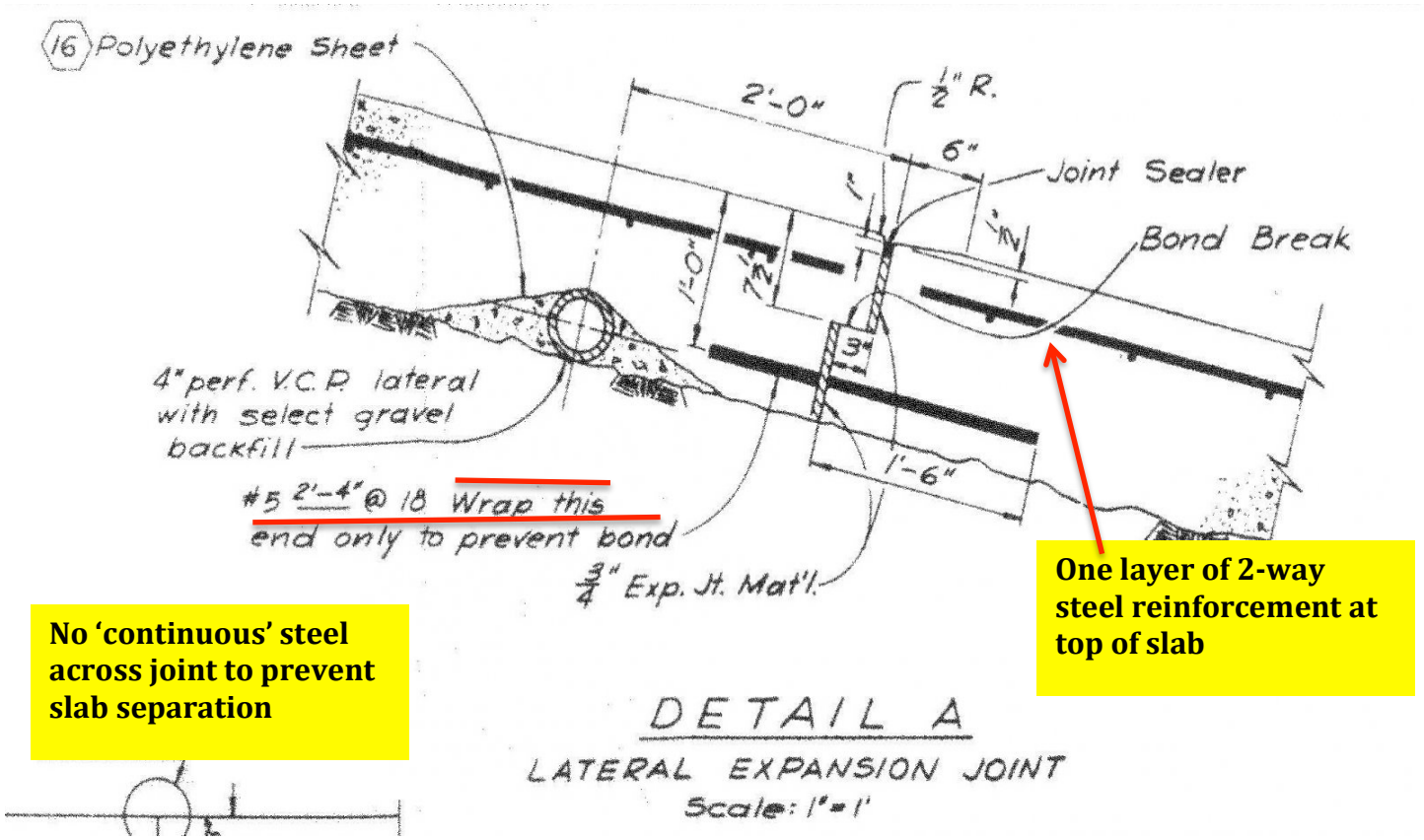
February 7, 2017 – Stage #1


Exposed rock and erodible sediments under spillway


Wall drains emptying water collected from under spillway

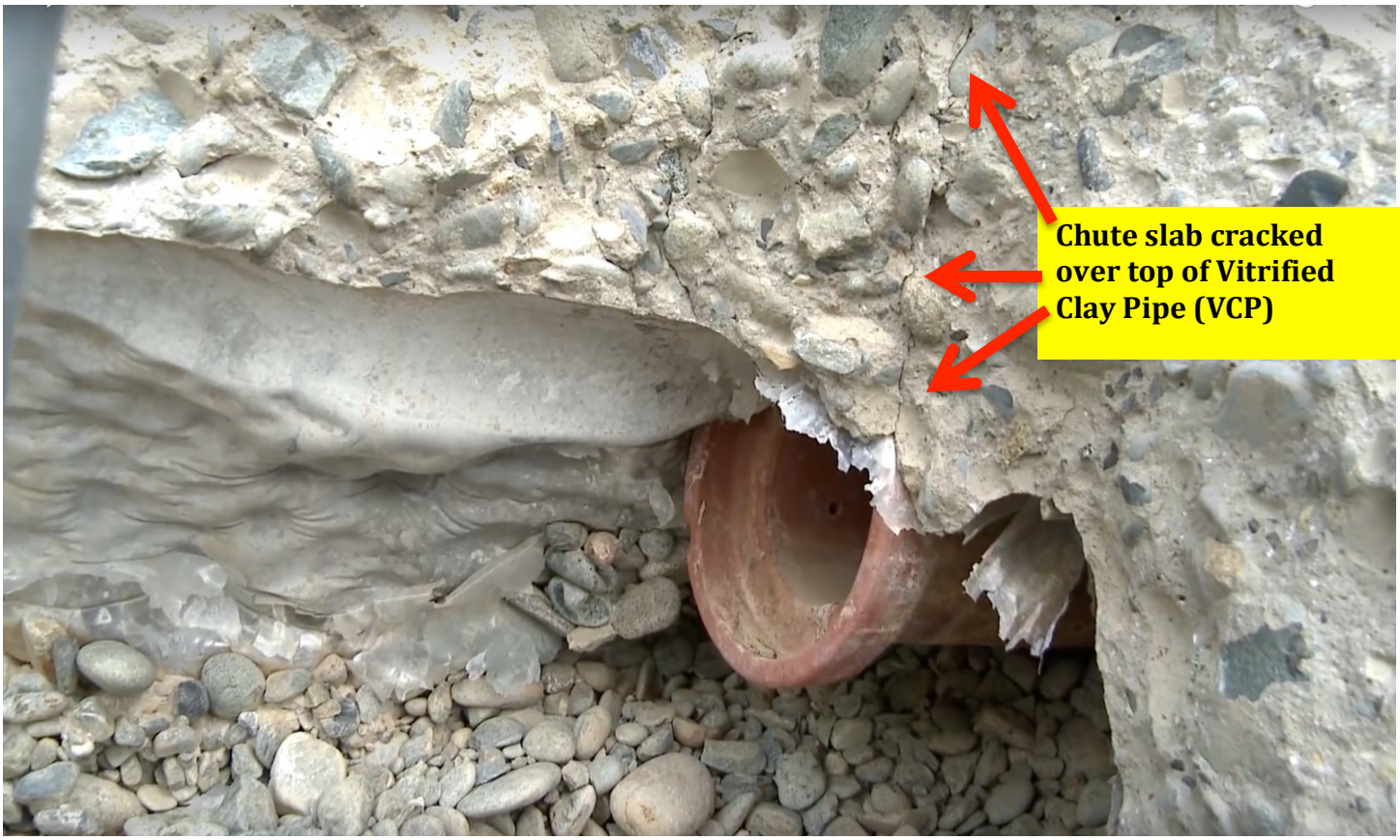

Wall drains on upper part of spillway indicate A Lot Of Water coming from under the spillway


Drains on 'herring bone' pattern under chute base slabs collect and discharge water to side wall drains



No 'continuous' steel across joint to prevent slab separation

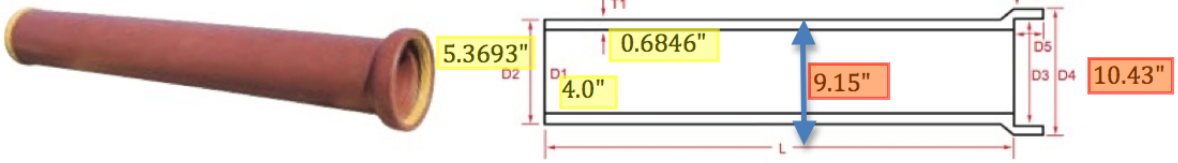
One layer of 2-way steel reinforcement at top of slab



Chute slab cracked over top of Vitrified Clay Pipe (VCP)

Standard Bell & Spigot

Oroville Design 1"=1' dwg dimension scale converted values for 4 inch pipe in drawings.

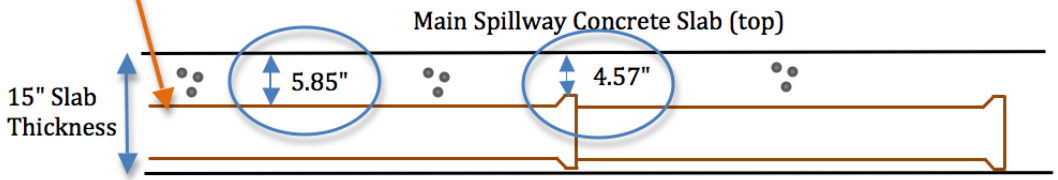


4.0" D1 | 5.3693" D2 | 0.6846" T1

D1	L	Weight plf	D2	D3	D4	D5	T1	T2
4"	1', 2', 4'	11 lb	5.3125"	6.5"	7.625"	1.5"	.6875"	.5"
6"	1', 2', 6'	21 lb	7.87"	9.05"	10.43"	2.33"	7.87"	0.67"

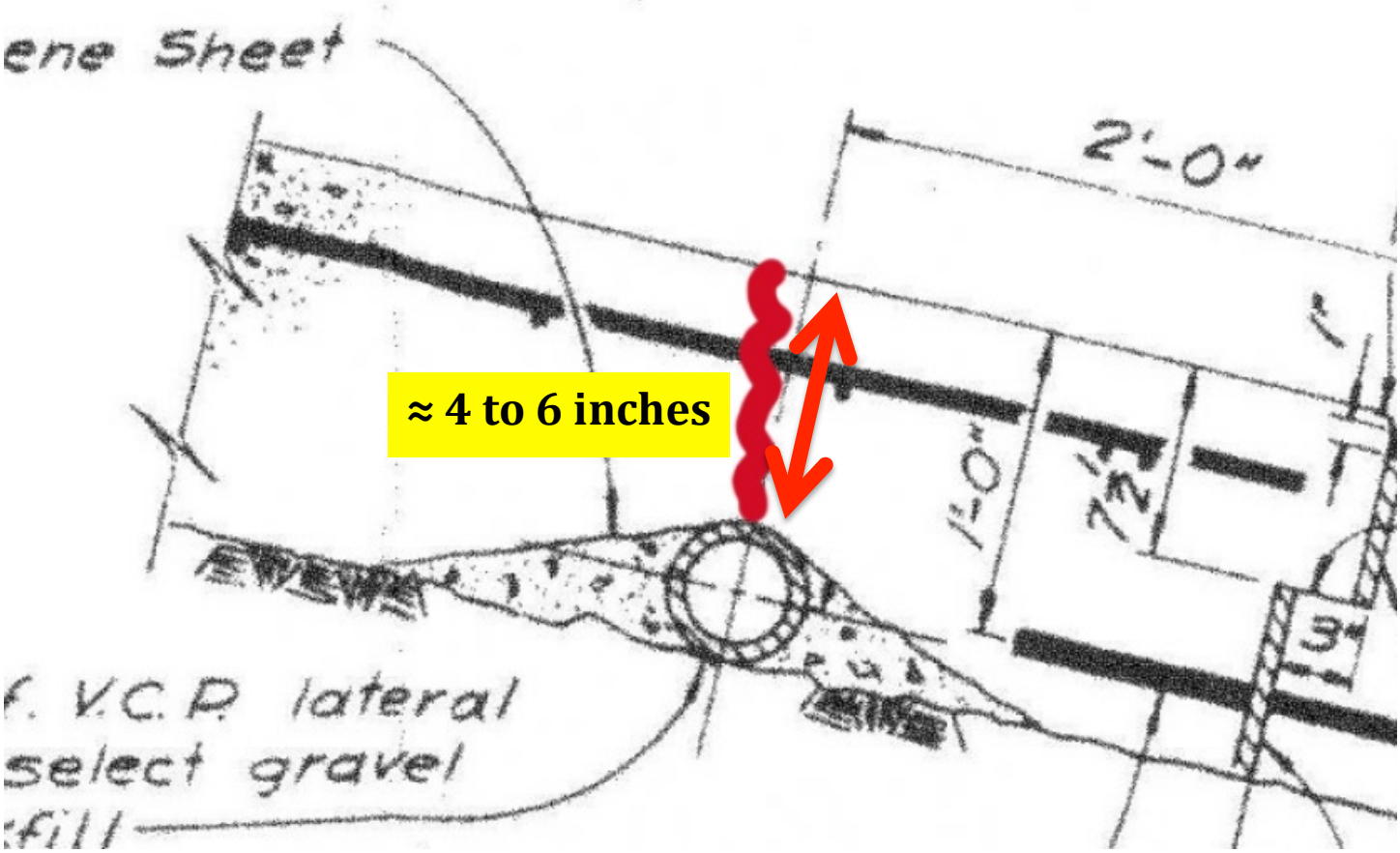
6" D1 | 7.87" D2 | 10.43" D4

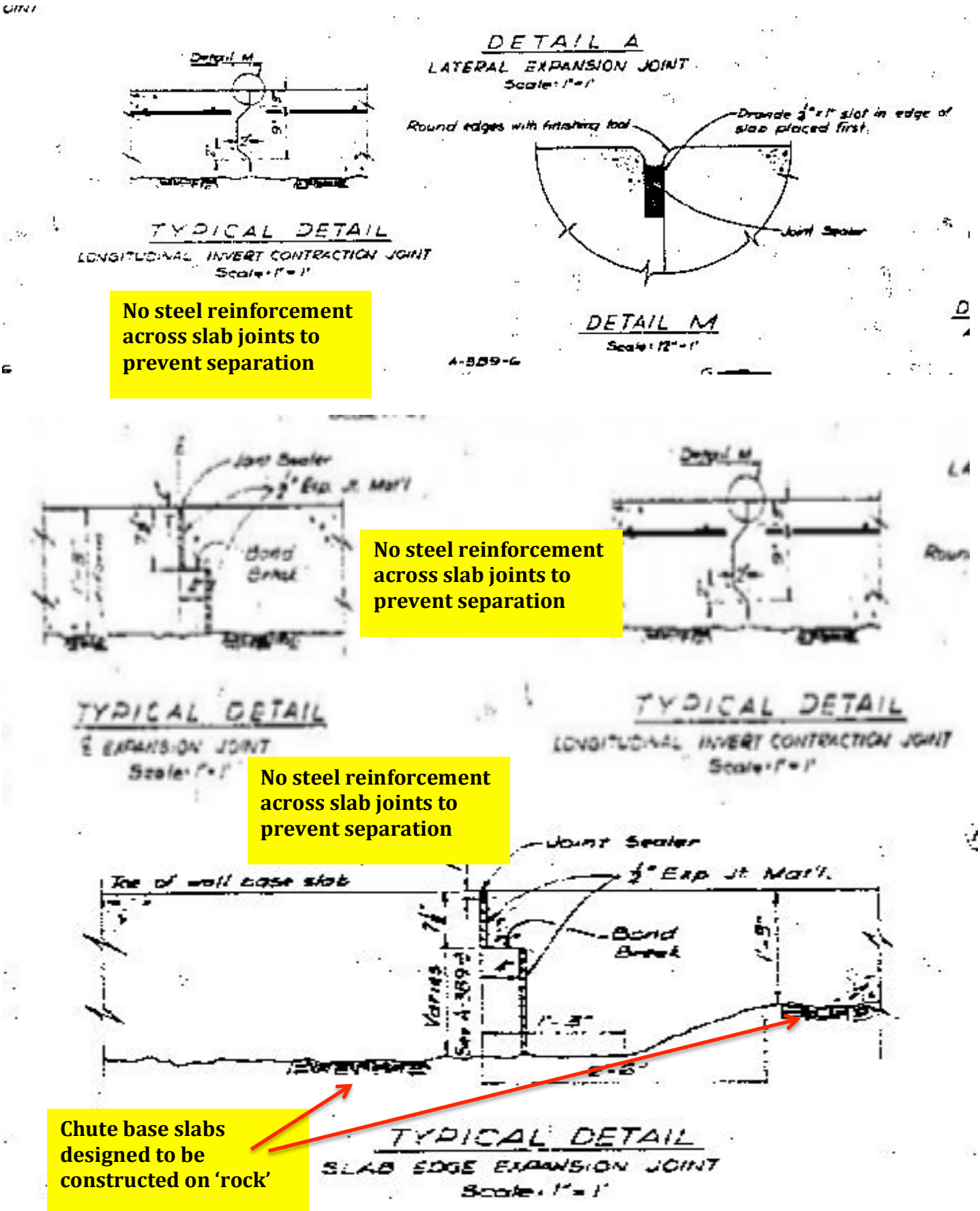
Spillway DESIGN Changed to 6" I.D. Drain Pipe: New dimensions should be very close to this table (6" D1, 7.87" D2, 10.43" D4)

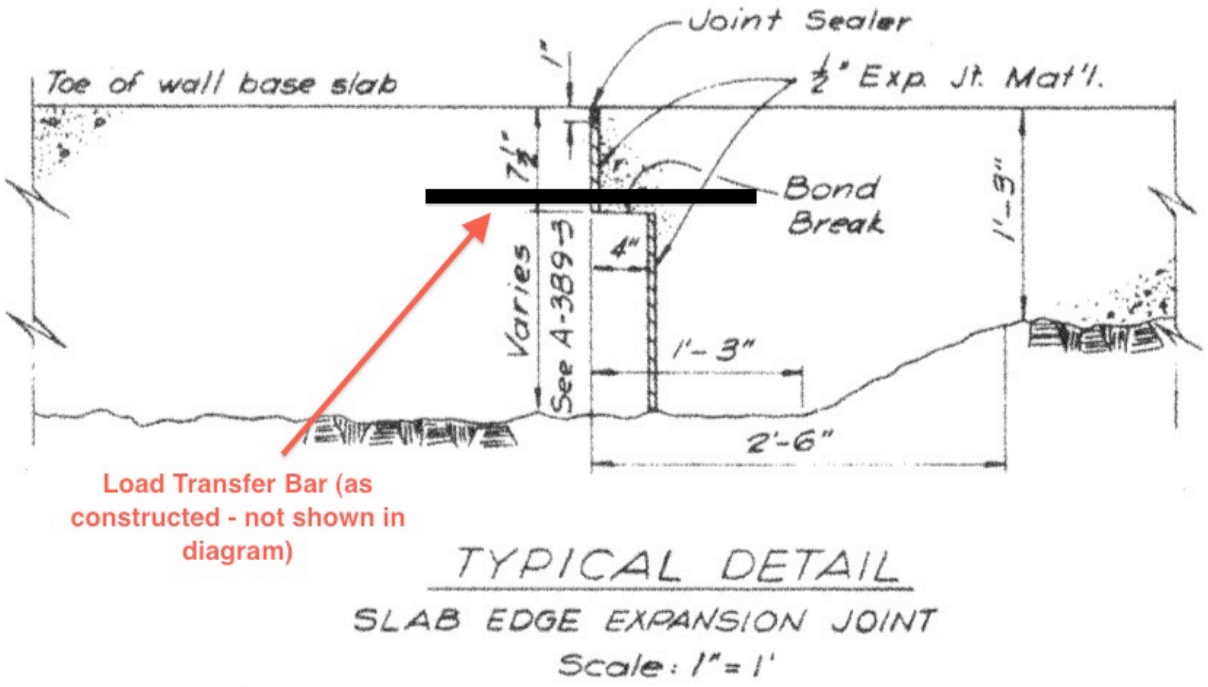


61% reduction in thickness

69.5% reduction in thickness




DETAIL A
LATERAL EXPANSION JOINT
Scale: 1"=1'
Round edges with finishing tool
Provide ¾"x1" slot in edge of slab placed first
Joint Sealer
DETAIL M
Scale: 12"=1'
TYPICAL DETAIL
LONGITUDINAL INVERT CONTRACTION JOINT
Scale: 1"=1'
No steel reinforcement across slab joints to prevent separation
Joint Sealer
½" Exp. Jt. Mat'l.
Bond Breaker
No steel reinforcement across slab joints to prevent separation
TYPICAL DETAIL
LONGITUDINAL INVERT CONTRACTION JOINT
Scale: 1"=1'
Joint Sealer
Toe of wall base slab
½" Exp Jt Mat'l.
Bond Breaker
Varies
No steel reinforcement across slab joints to prevent separation
Chute base slabs designed to be constructed on 'rock'
TYPICAL DETAIL
SLAB EDGE EXPANSION JOINT
Scale: 1"=1'

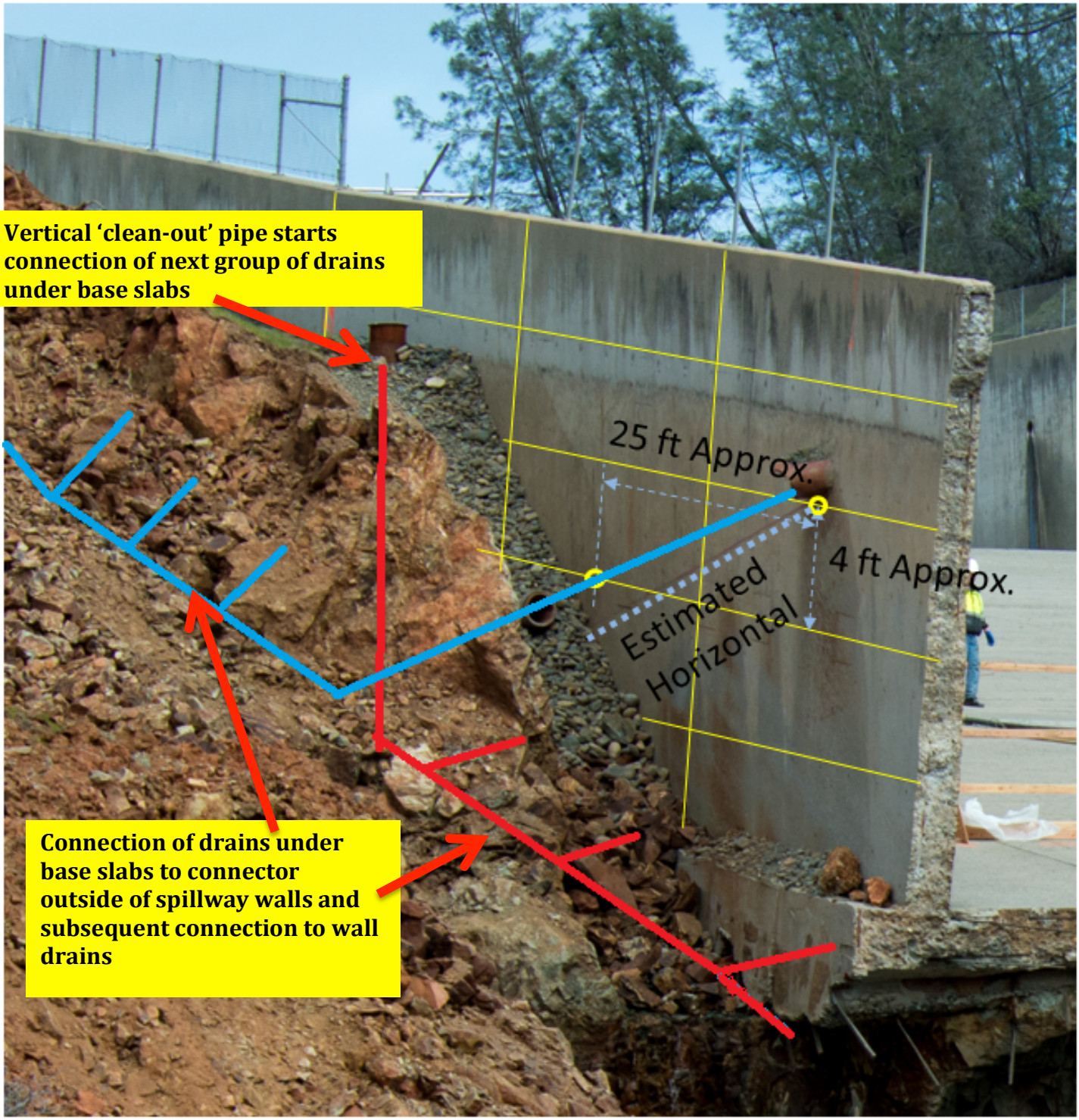


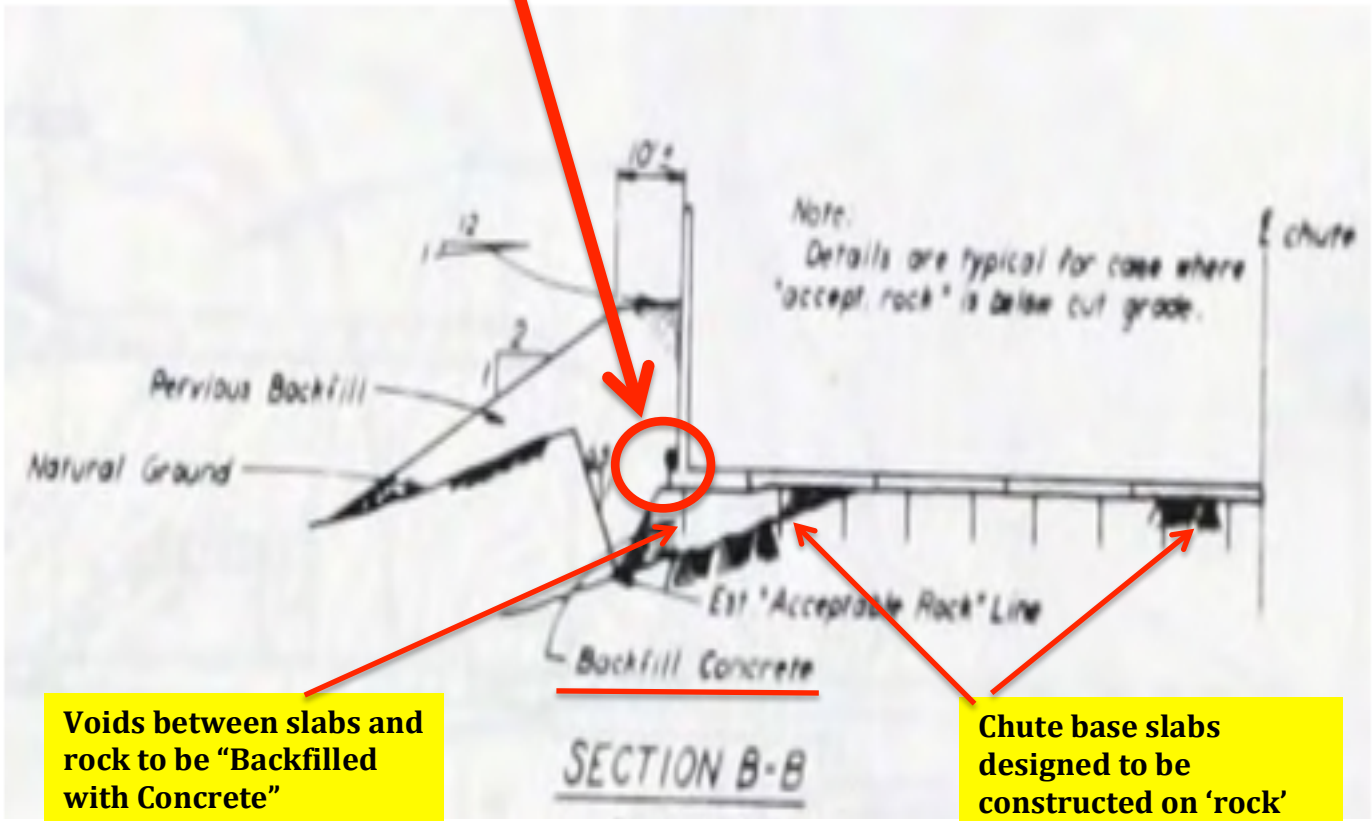
TYPICAL DETAIL

SLAB EDGE EXPANSION JOINT

Scale: 1" = 1'


Water flow pattern indicates slabs displaced vertically


Vertical 'clean-out' pipe starts connection of next group of drains under base slabs
25 ft Approx.
4 ft Approx.
Estimated Horizontal
Connection of drains under base slabs to connector outside of spillway walls and subsequent connection to wall drains



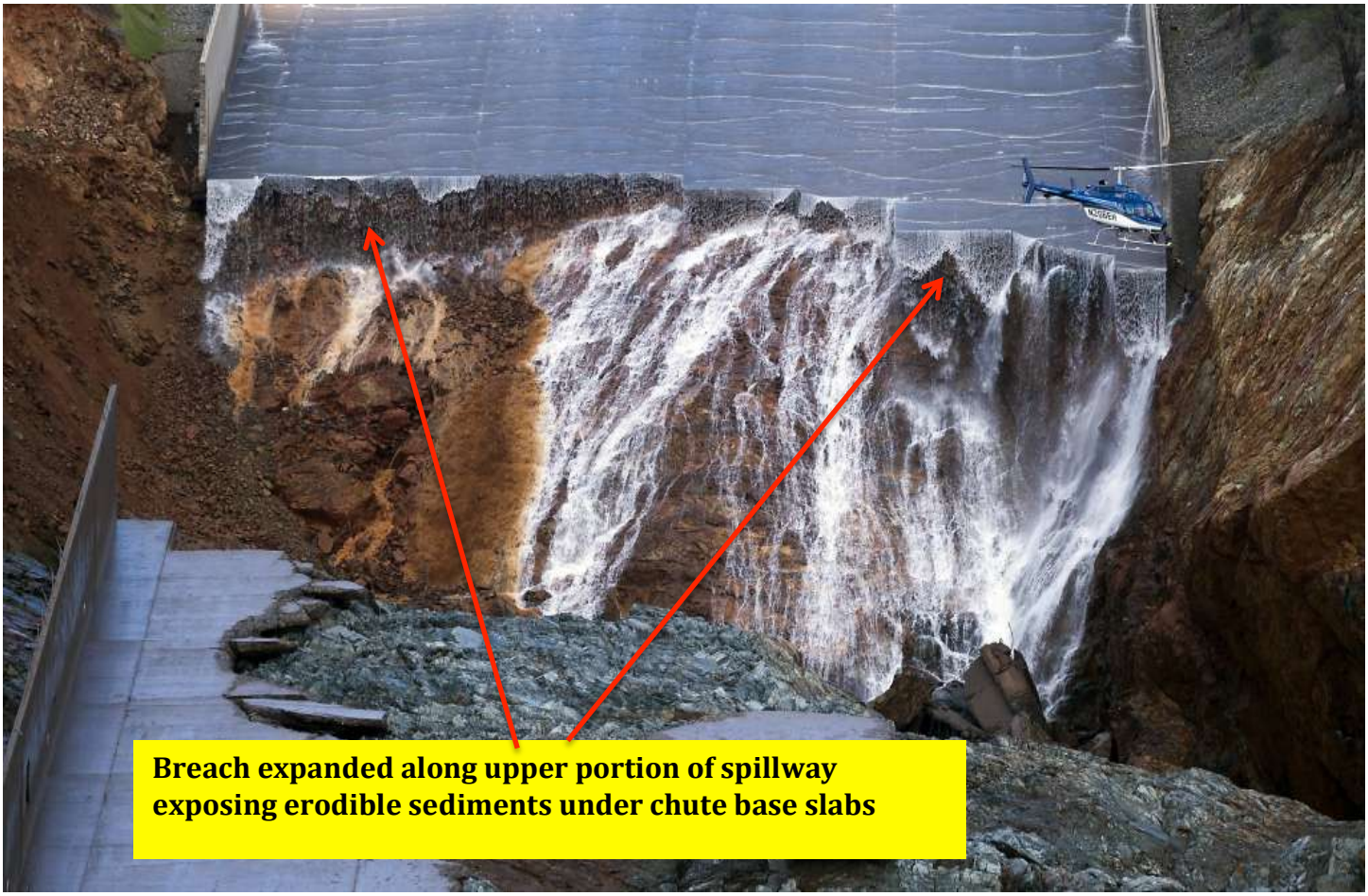
Voids between slabs and rock to be "Backfilled with Concrete"

Chute base slabs designed to be constructed on 'rock'

February 9, 2017 – Stage #2


Wall drain flowing ‘dirty’ water from under spillway with suspended sediments


Both sides of spillway chute walls breached and eroding sediment outside of spillway


Breach expanded along upper portion of spillway
exposing erodible sediments under chute base slabs


'Incompetent' weathered rock
'Competent' non-weathered rock


'Incompetent' weathered rock

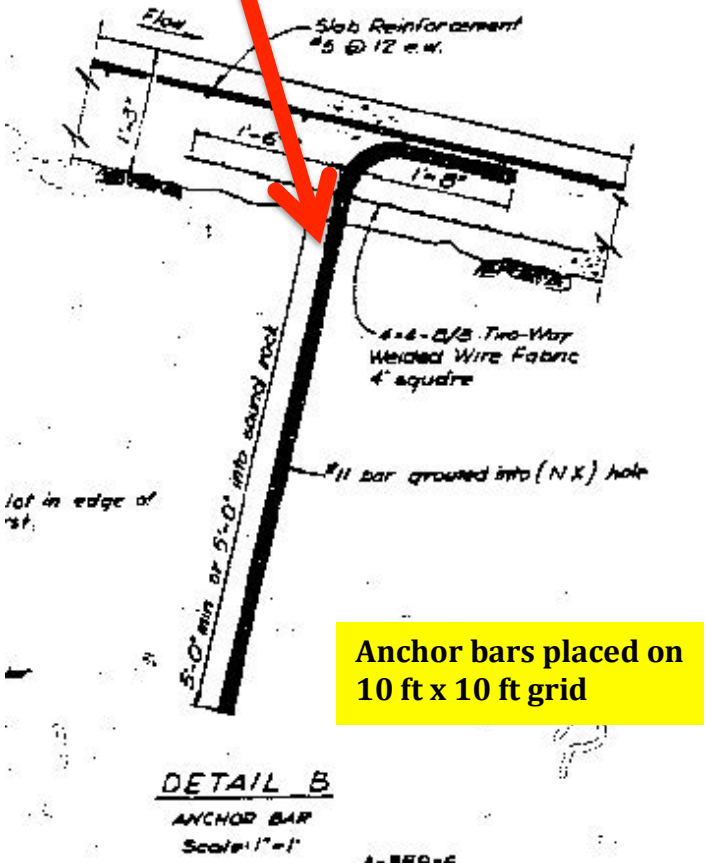
Stage 3 – February 16, 2017


Soils eroded from under slabs


Eroded concrete surface exposing reinforcing steel - indicates water scouring 'cavitation' effects
Slab cracks


One layer of 2-way steel reinforcement at top of chute slabs


One layer of 2-way steel
reinforcement at top of base slabs



Anchor bars placed on 10 ft x 10 ft grid

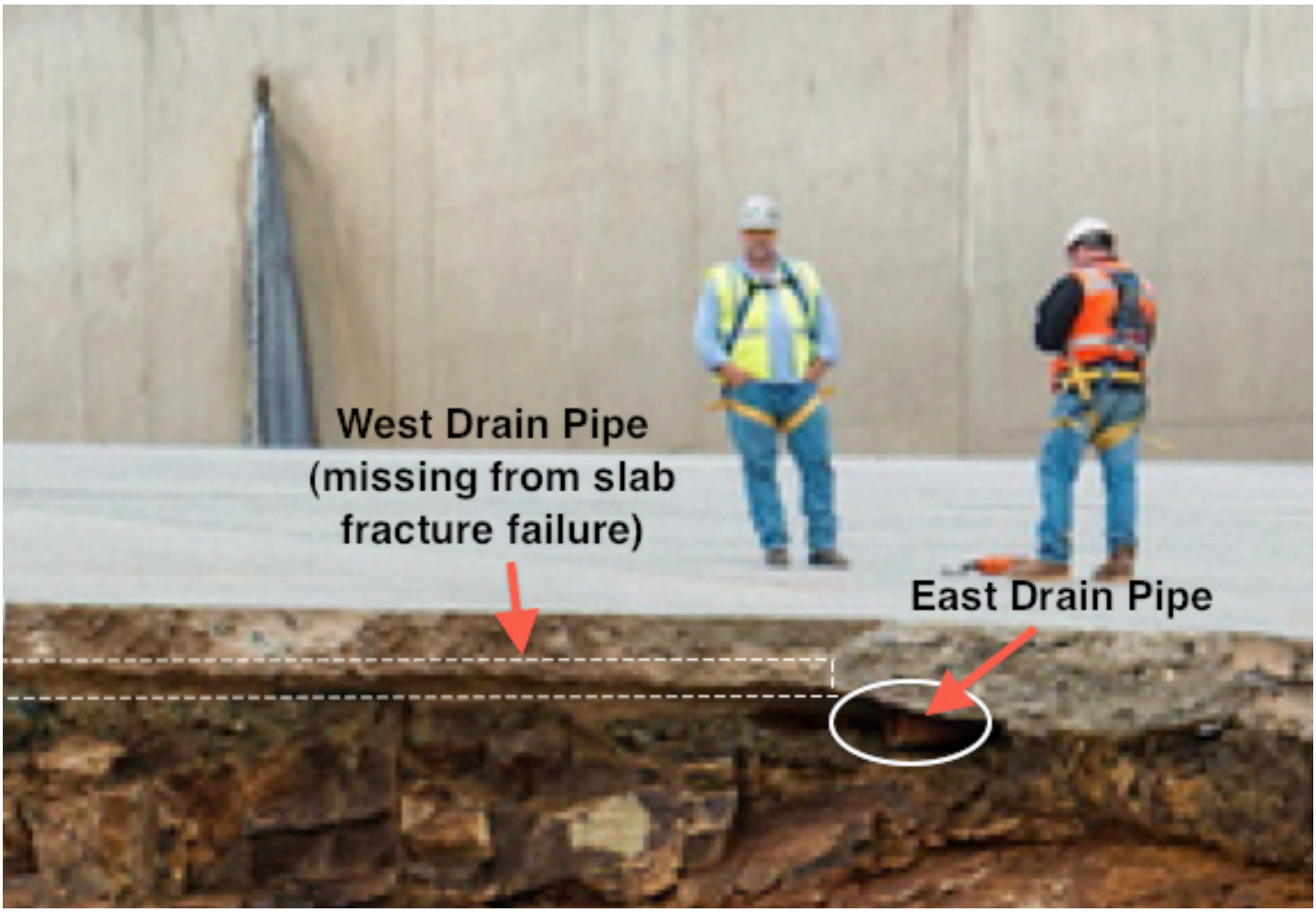
Stage #4 – Temporary Repairs to spillway chute


DANGER
FALL PROTECTION
REQUIRED IN
THIS AREA


Leakage water draining into transverse joints

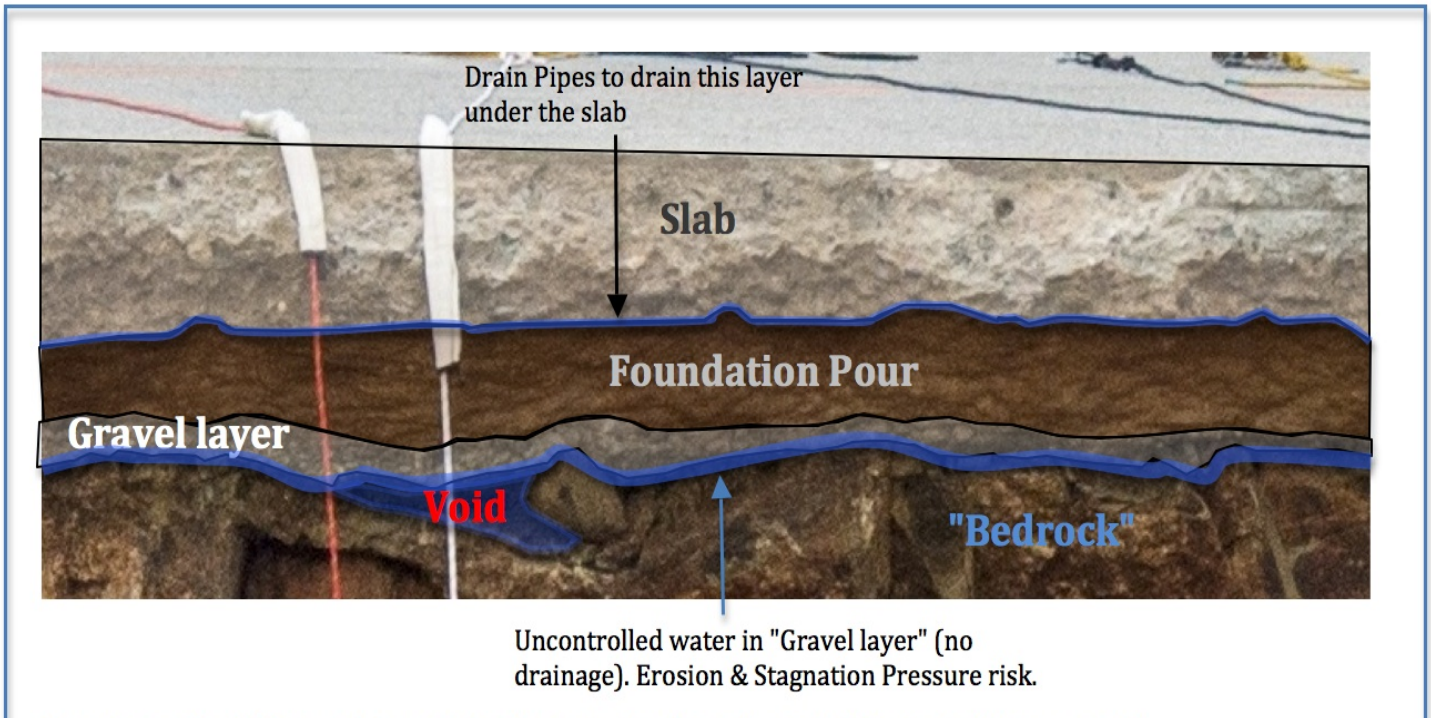

Concrete fractured along
drain pipe emplacement


Flanged steel pipe under chute base slab ?

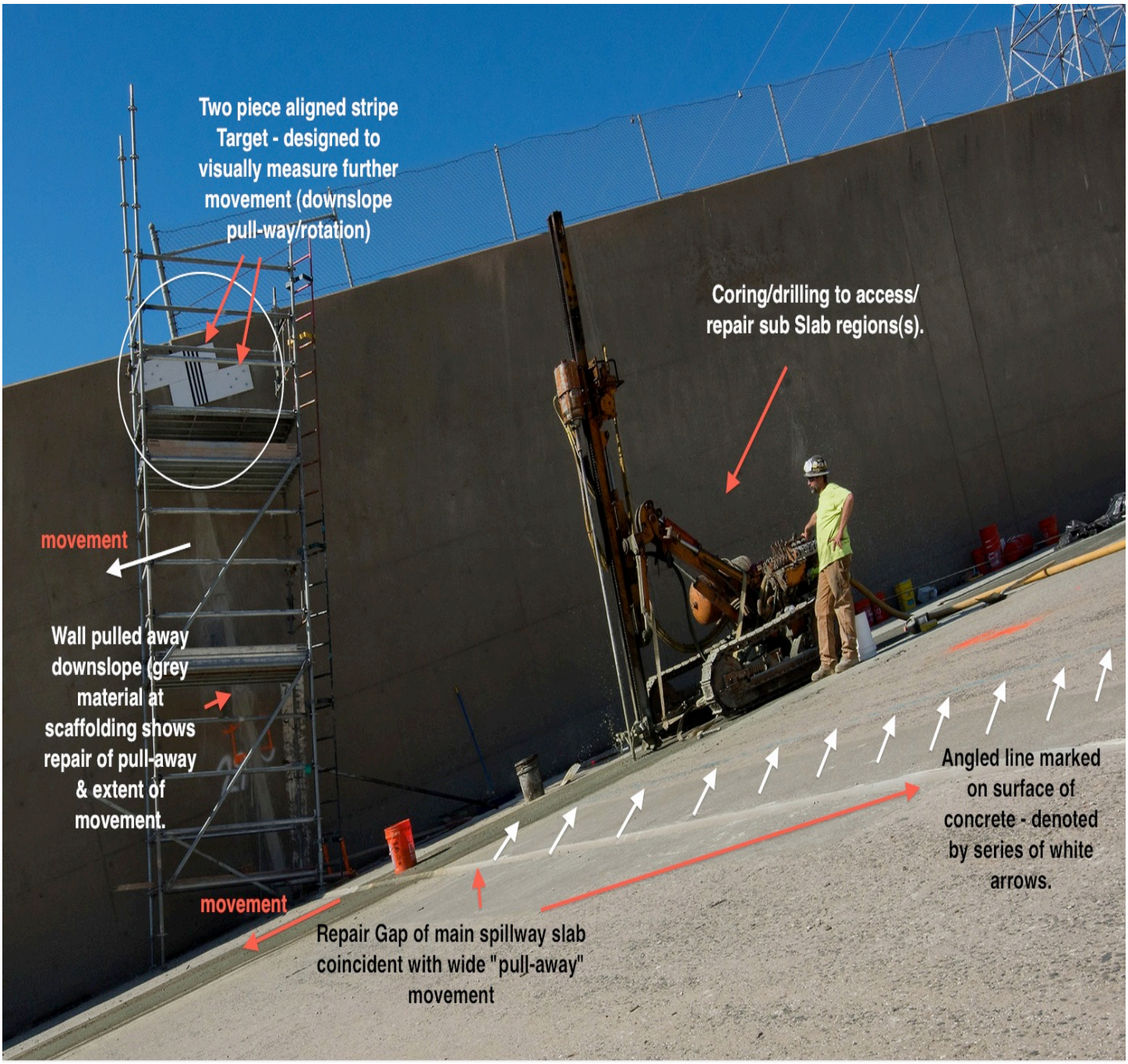

West Drain Pipe
(missing from slab
fracture failure)
East Drain Pipe

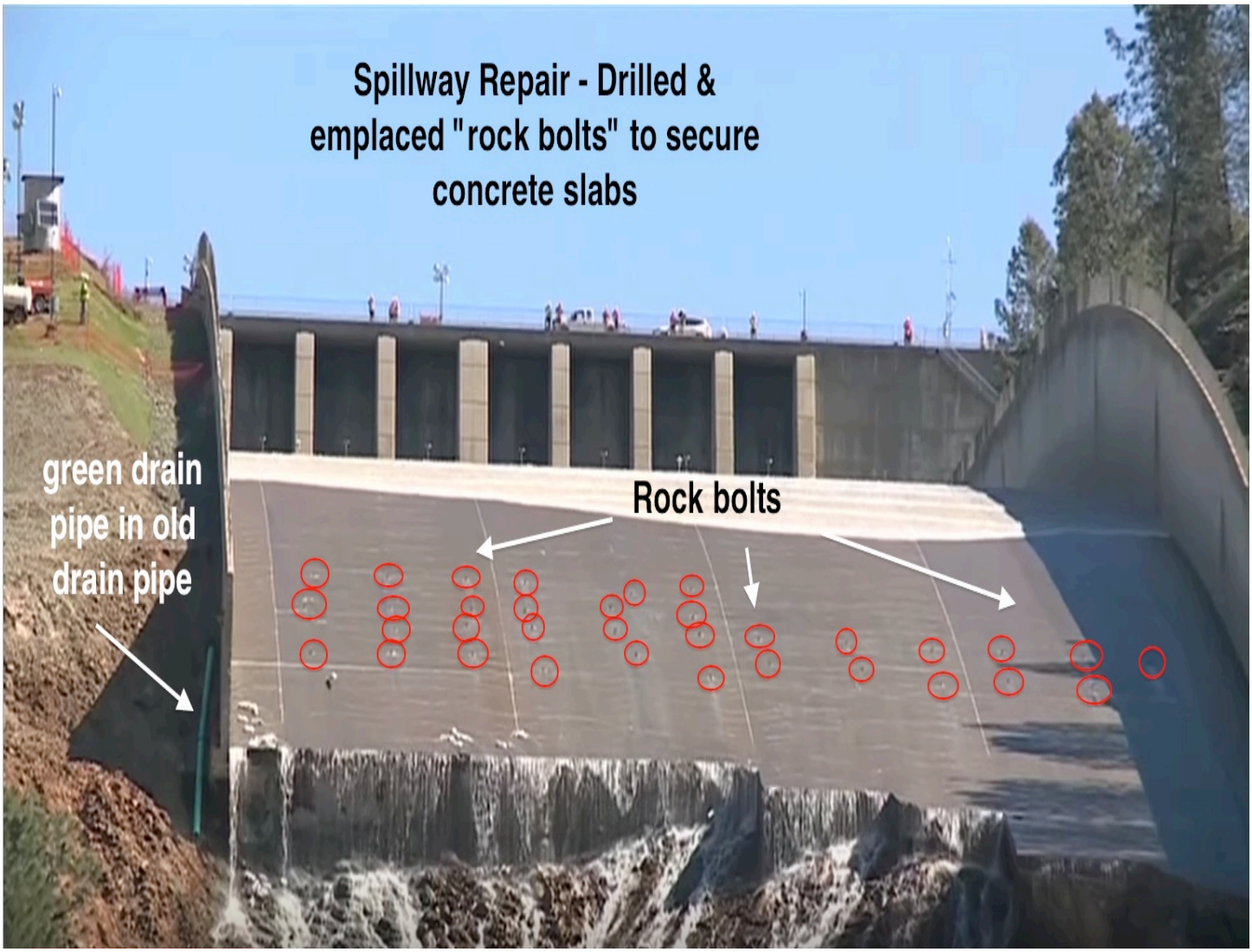

West Drain Pipe outline created by Pipe
+ Polyethelene Plastic + emplacement
gravel
Gravel retained from
penetrating concrete
Waterflow seams and
Voids deeper Under
Drain Pipe


Voids deeper under Drain Pipe (possible source of water induced weathering of rock - leading to large pockets of weakened base rock)


Drain Pipes to drain this layer under the slab
Slab
Foundation Pour
Gravel layer
Void
"Bedrock"
Uncontrolled water in "Gravel layer" (no drainage). Erosion & Stagnation Pressure risk.


"pulling away" gap in wall and spillway slab.
gap narrowing further down spillway indicates a "rotation"
Erosion of foundation base of wall from broken drain at 5th fence post behind spillway wall.
Rotation indicators of section of main spillway (gaps, broken drain erosion on wall foundation, and spillway backcutting).

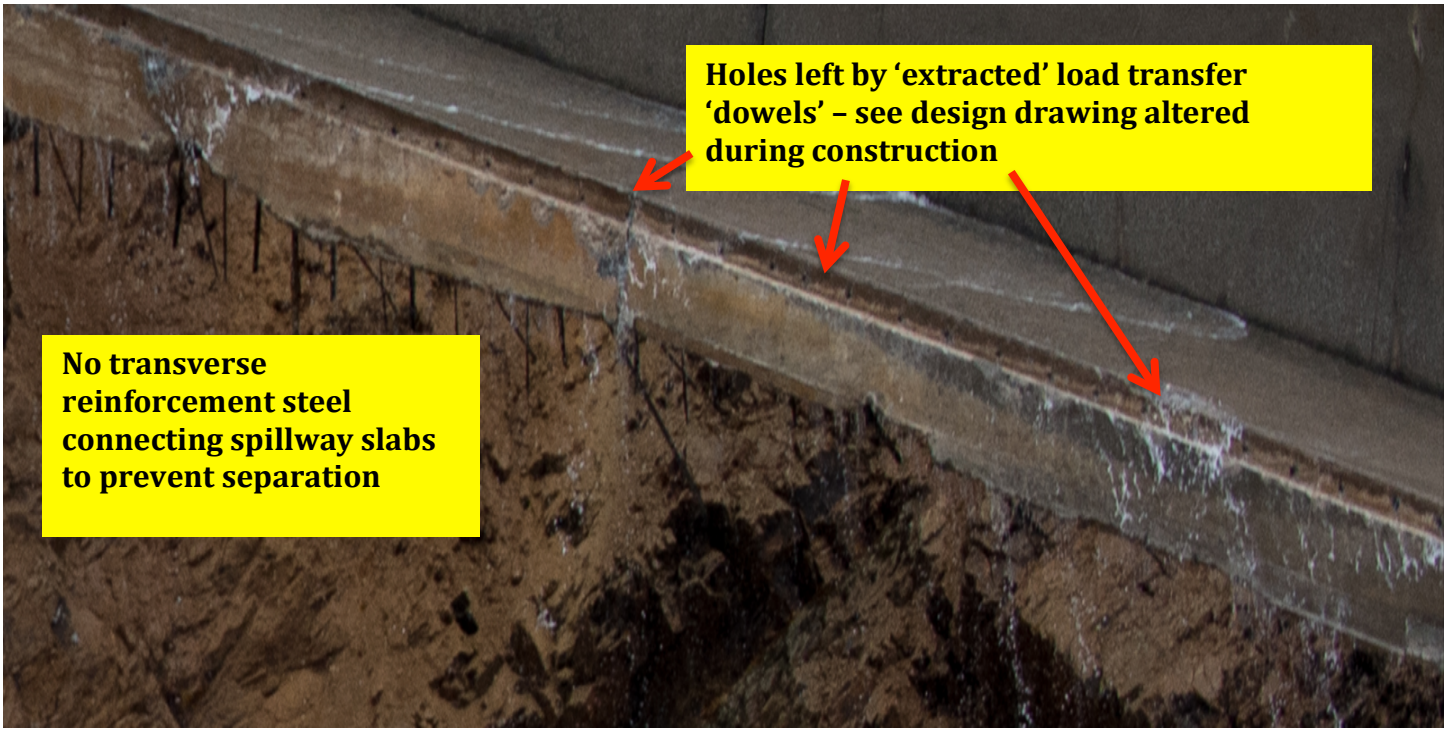

Two piece aligned stripe Target - designed to visually measure further movement (downslope pull-way/rotation)
Coring/drilling to access/ repair sub Slab regions(s).
movement
Wall pulled away downslope (grey material at scaffolding shows repair of pull-away & extent of movement.
Angled line marked on surface of concrete - denoted by series of white arrows.
movement
Repair Gap of main spillway slab coincident with wide "pull-away" movement

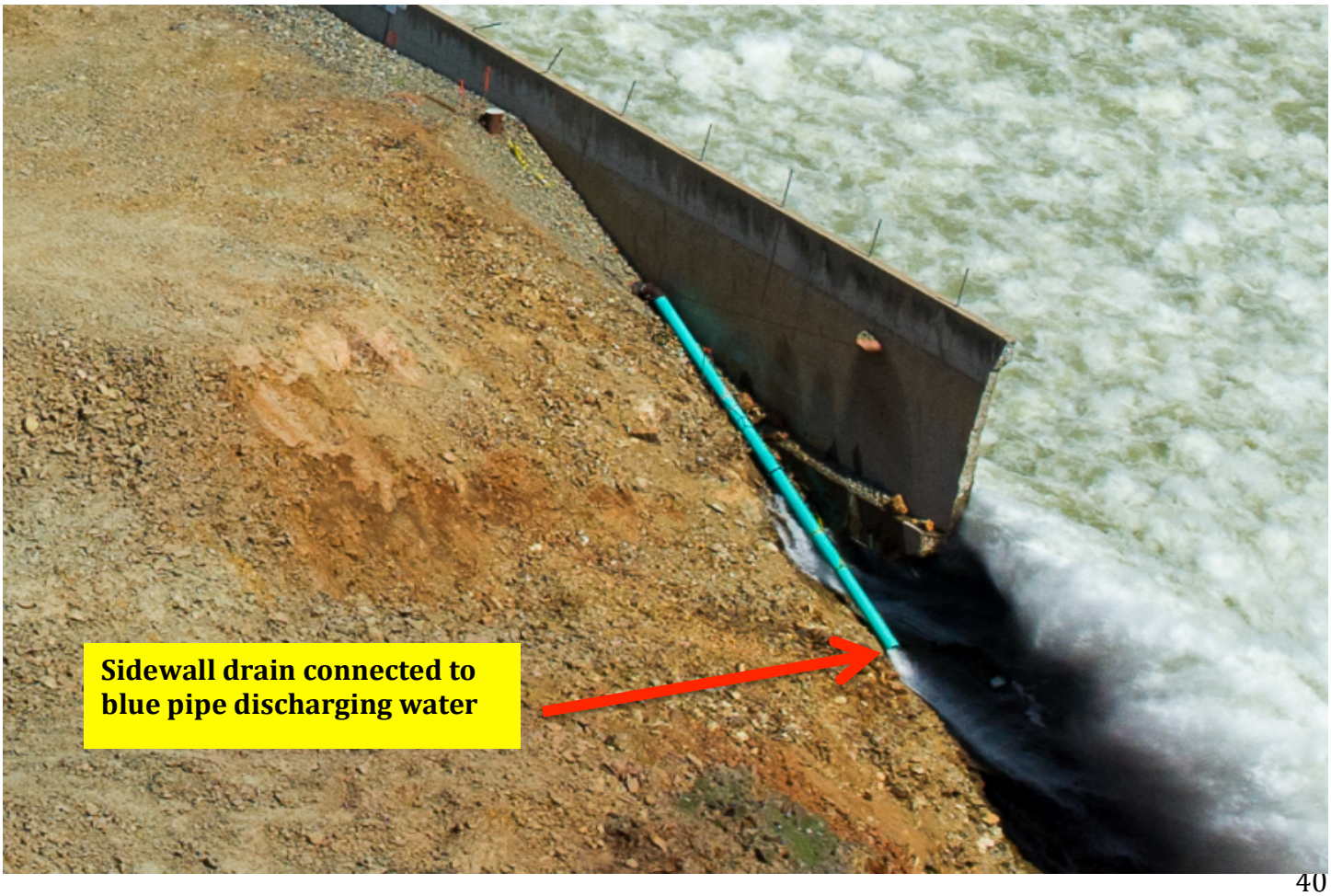

Spillway Repair - Drilled & emplaced "rock bolts" to secure concrete slabs
green drain pipe in old drain pipe
Rock bolts


No longitudinal reinforcement steel connecting spillway slabs to prevent separation


No longitudinal reinforcement steel connecting spillway slabs

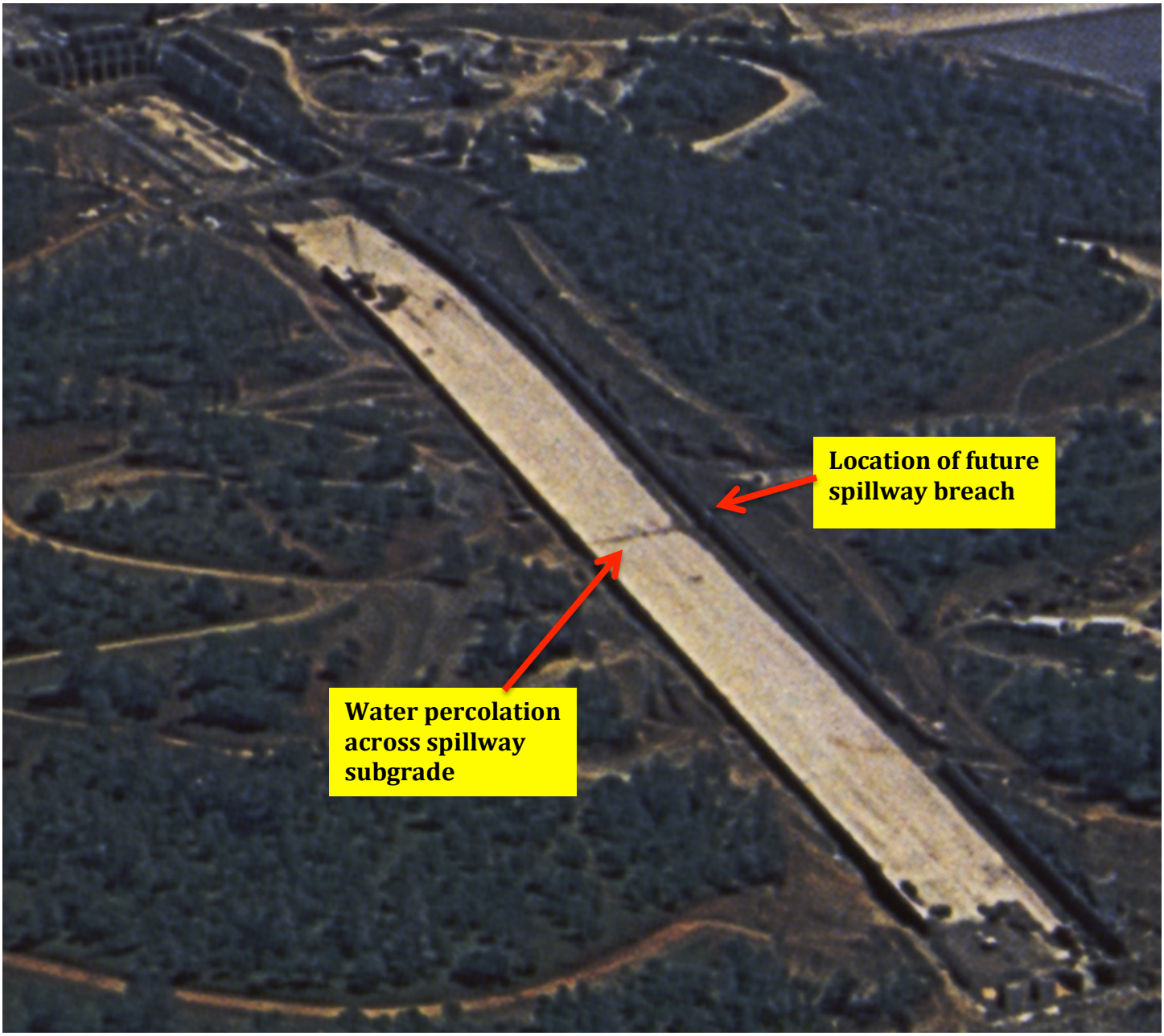

No transverse reinforcement steel connecting spillway slabs to prevent separation


Holes left by ‘extracted’ load transfer ‘dowels’ – see design drawing altered during construction
No transverse reinforcement steel connecting spillway slabs to prevent separation


Sidewall drain connected to blue pipe discharging water

Pre-Failure Images

1967 – Spillway being constructed – walls being cast – chute subgrade placed

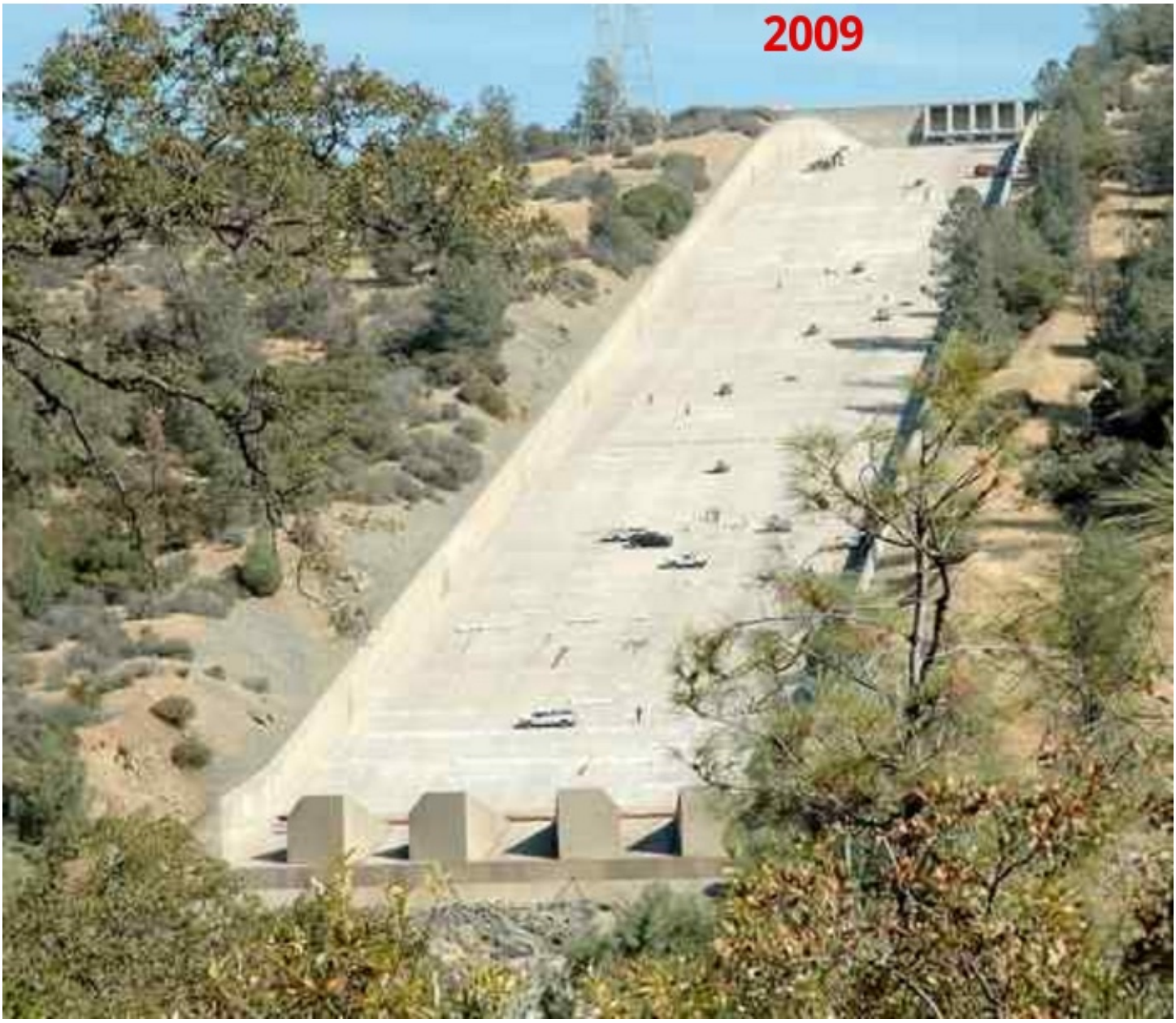

Location of future spillway breach
Water percolation across spillway subgrade

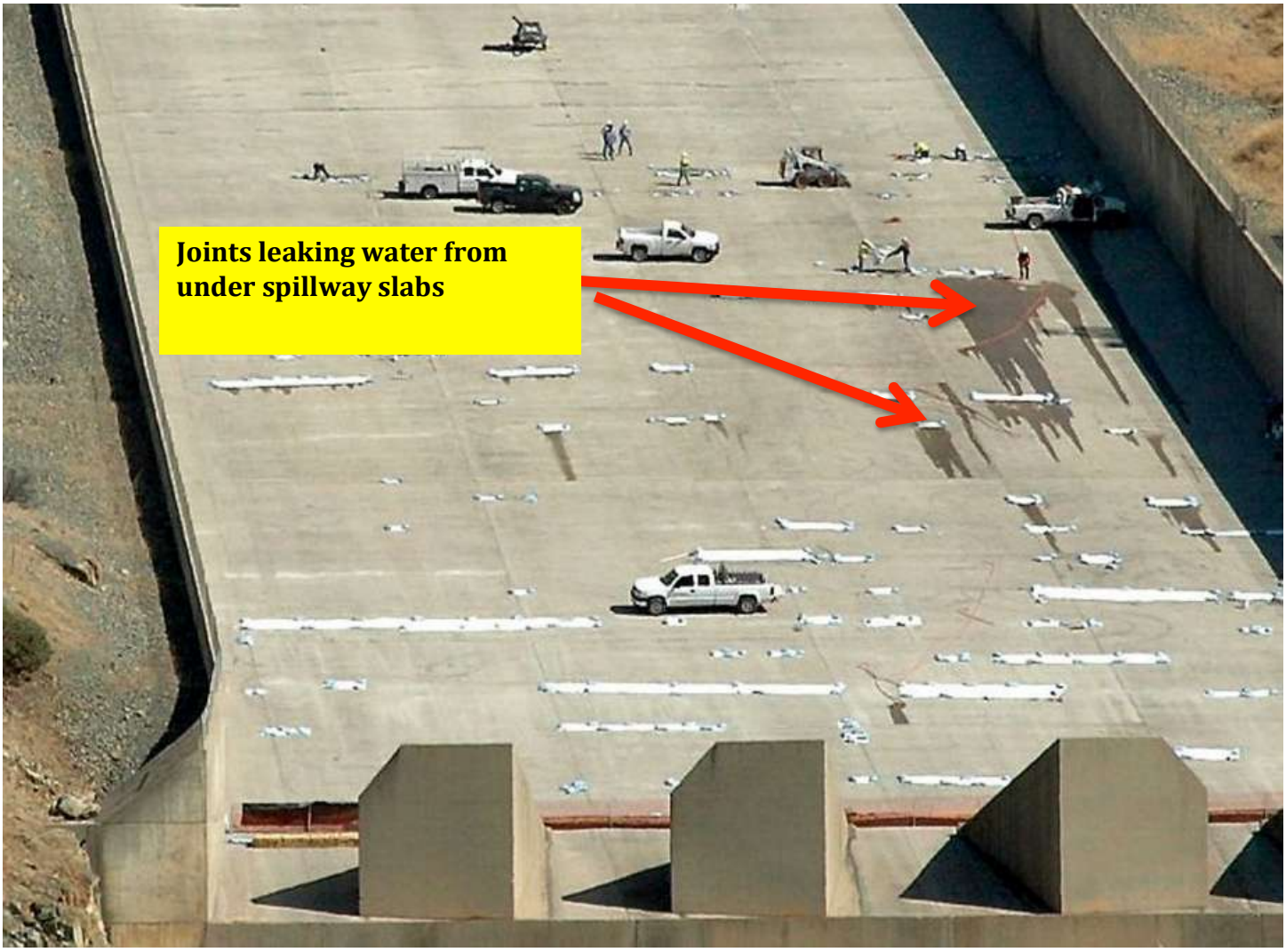
August 4, 1969

November 9, 2007


2007 USGS

October 7, 2009 – Repairs being made to spillway base slabs




Joints leaking water from under spillway slabs

July 9 - 10, 2010


7/9/2010
1998
2015
Cracks in spillway chute slabs
Large trees growing adjacent to spillway wall – roots able to penetrate and plug drains
Google Earth
1998
Imagery Date: 7/9/2010 10 S 629099.39 m E 4377636.00 m N elev 540 ft eye alt 404 ft


7/9/2010
1998
2015
Cracks in spillway discharge slabs
Google Earth
1998
Imagery Date: 7/9/2010 10 S 628915.57 m E 4377441.75 m N elev 327 ft eye alt 404 ft

2012

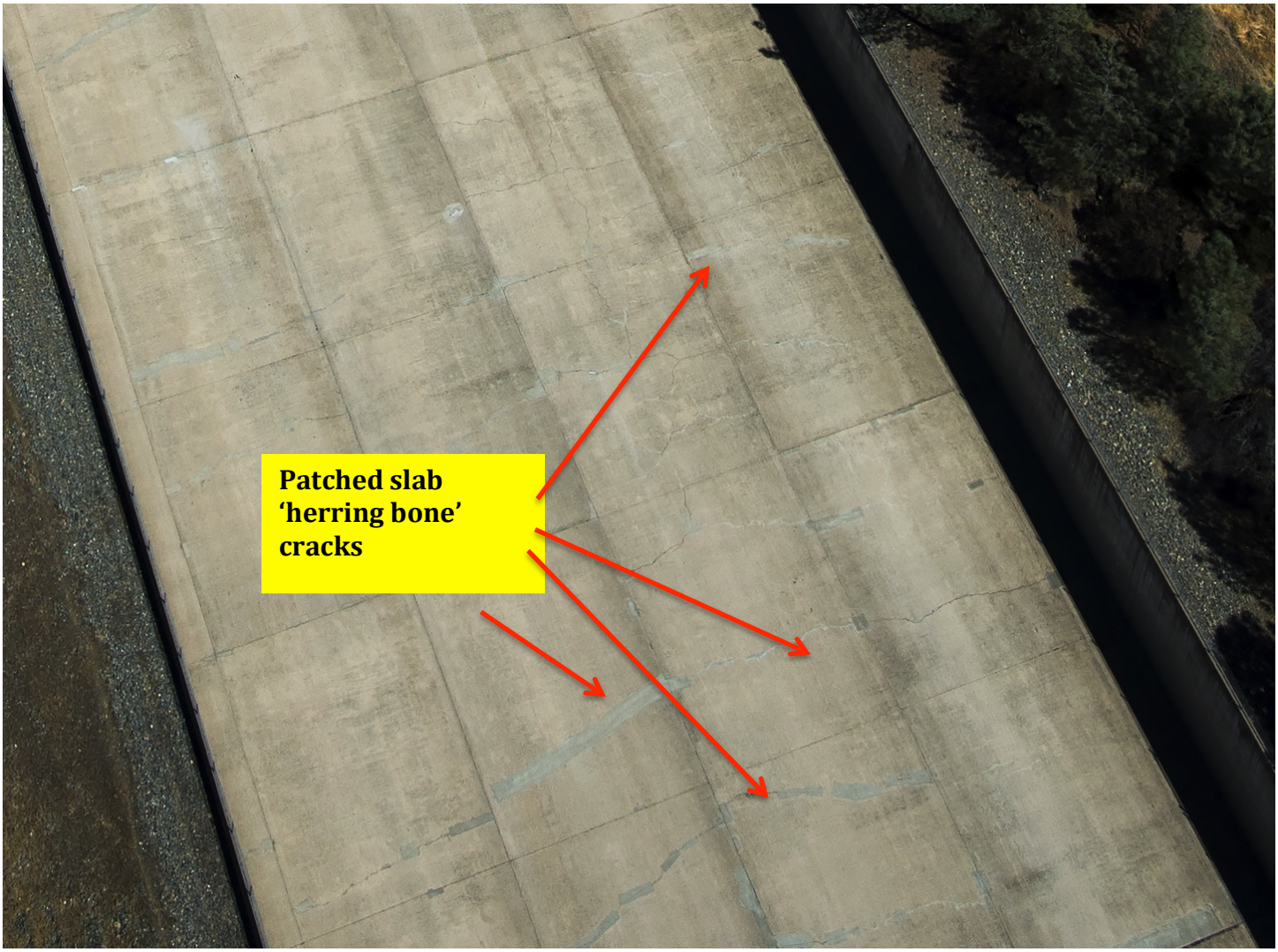

Wall drain not flowing - plugged
Slab edges displaced vertically (circled)
Large trees growing adjacent to spillway wall – roots able to penetrate and plug drains

2013


Repairs underway to chute contraction joint at future site of breach.


2013
Repairs underway on chute contraction joint at future site of breach.
Water seeping through joints from under chute slabs.
Large trees growing adjacent to spillway wall – roots able to penetrate drains

September 5, 2014


Patched slab
'herring bone'
cracks

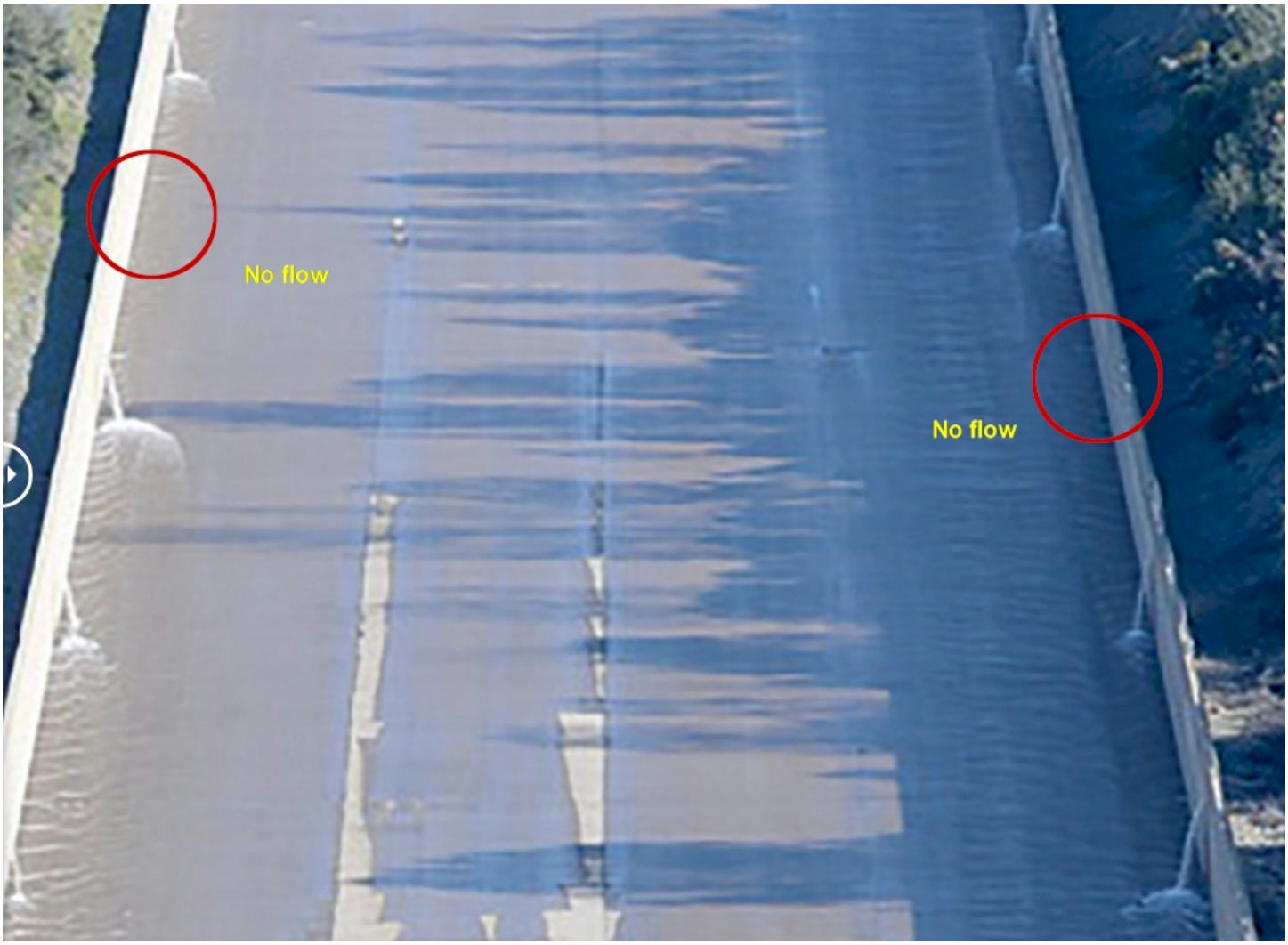

2014

April 14, 2015


Google Earth
100 ft
N

March 2016

January 27, 2017


No flow
No flow

Previous inspection report photographs

5/6/08 Inspection Report

11. The spillway at the flood control outlet remains in satisfactory condition.

12/14/09 Inspection Report

20. This view shows the flood control outlet chute as seen from the upper deck. The walls and chute appeared to be stable and in satisfactory condition. Minor repairs along the chute floor will be completed this year.

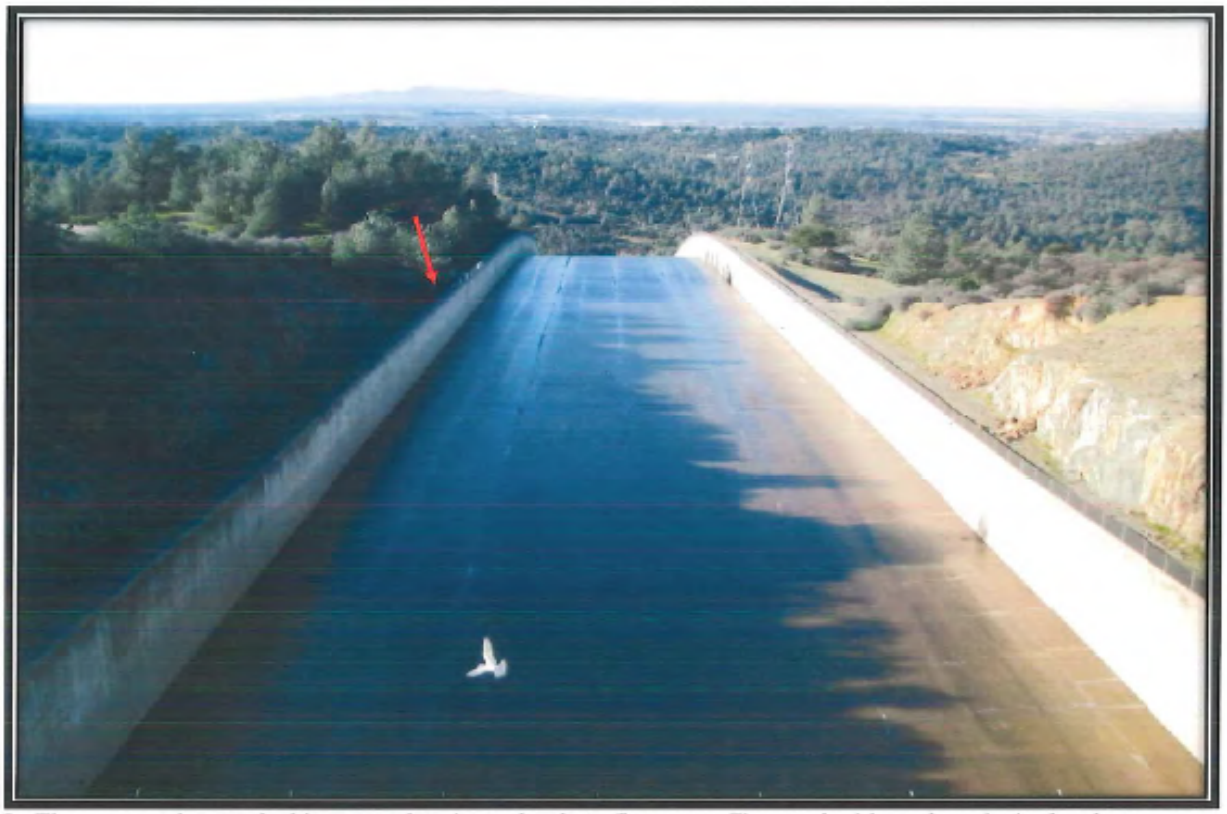
21. The lower flood control outlet chute is shown. Not the markings for the upcoming chute repairs.

6/25/10 Inspection Report

12. The concrete along the spillway chute has been repaired. The repaired herringbone crack pattern is said to reflect the underlying drain system.

Oroville Dam, No. 1-48

2/8/11 Inspection Report



9. The gates seals were leaking enough to keep the chute floor wet. The repaired lateral cracks in the chute floor are visible as light streaks. The brush at the arrow should be removed to prevent root invasion of the wall drain. No signs of instability were noted along the chute walls or floor. The drain holes at the end of the chute were flowing.

2/16/11 Inspection Report

11. The flood control outlet flow pattern was normal. The walls were well aligned and stable appearing. The drains at the vertical curve along the chute were flowing as expected. The brush growing in the backfill gravel adjacent to the left wall should be removed as previously requested. See arrow at left.

2/5/13 Inspection Report

14. The flood control outlet gate seal leakage and drain flow are visible. The trees and brush shown within the ovals should be removed by November 1, 2013.

Oroville Dam, No. 1-48

9/8/14 inspection report

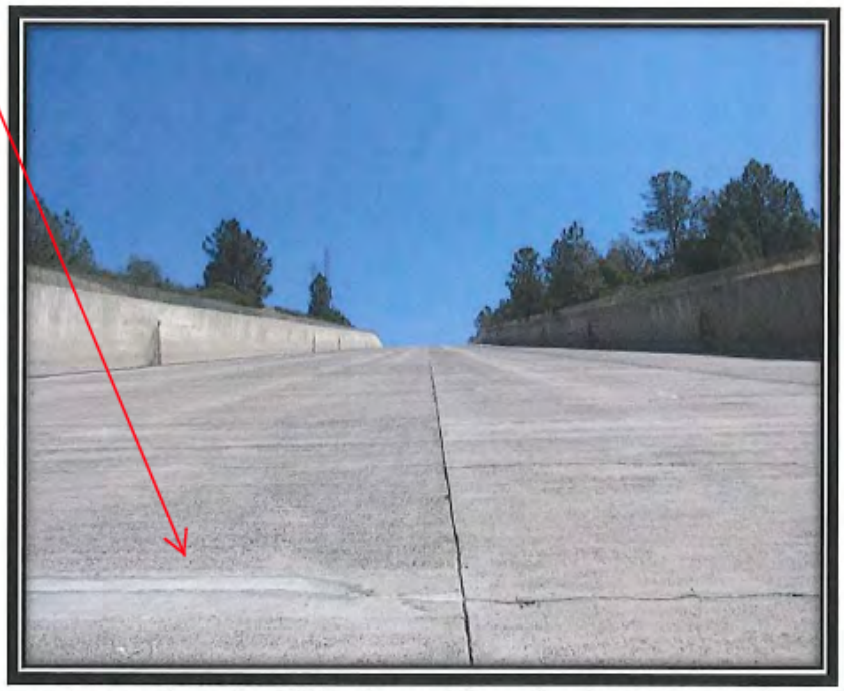
12. The FCO channel appeared to be in satisfactory condition. The walls were well aligned and the patches along the chute floor remain intact.

13. This view is looking upstream along the FCO channel from the dentates. Dark, vertical stains along the walls indicate the location of the drain outfalls.

2/3/15 inspection report

9. This view looking upstream along the FCO discharge chute shows one tree (arrow) that needs to be removed following a significant effort to remove brush along the outside of the wall.

12. The FCO channel appeared to be in satisfactory condition. The walls were well aligned and the patches along the chute floor remain intact.



13. This view is looking upstream along the FCO channel from the dentates. Dark, vertical stains along the walls indicate the location of the drain outfalls.

9. This view looking upstream along the FCO discharge chute shows one tree (arrow) that needs to be removed following a significant effort to remove brush along the outside of the wall.

2014 Bureau of Reclamation spillway design cross sections

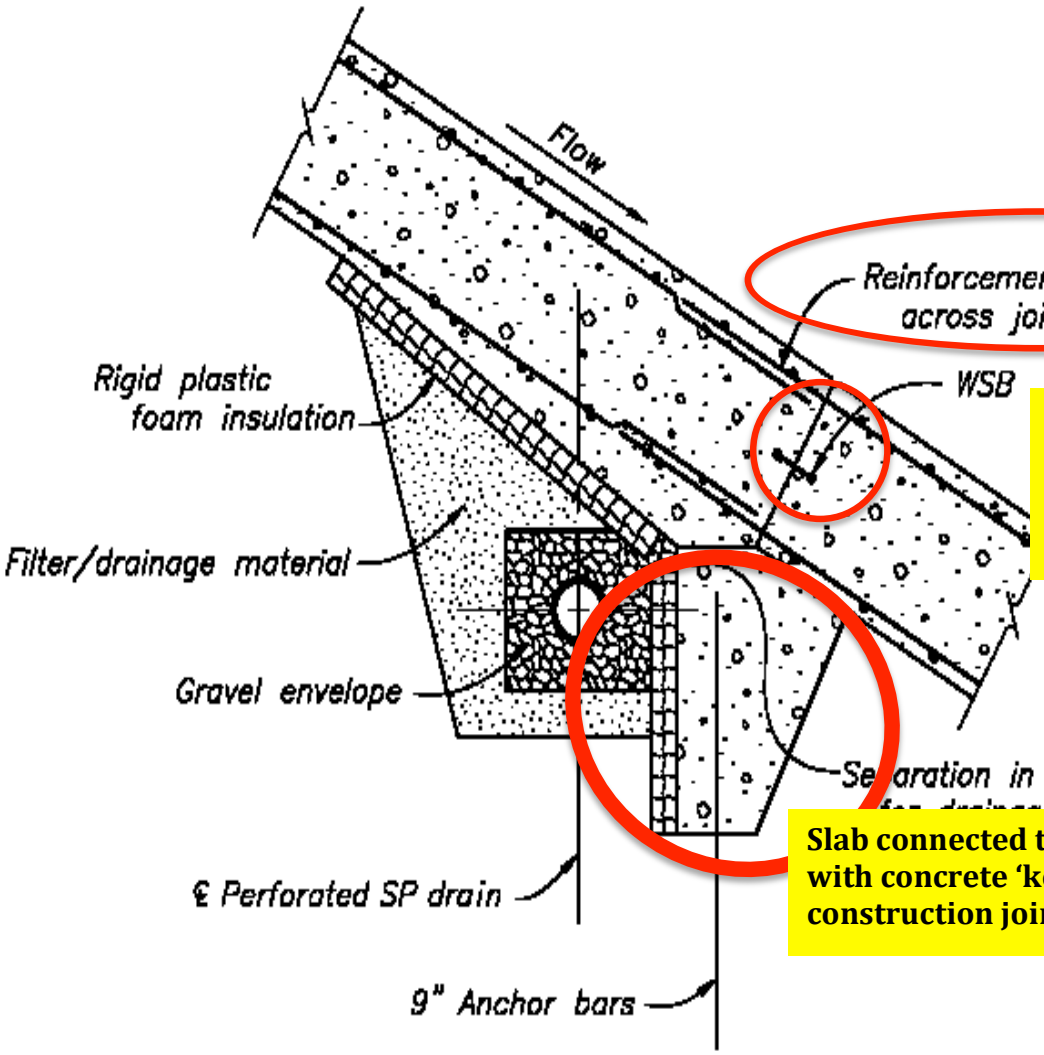
RECLAMATION
Managing Water in the West

Design Standards No. 14
Appurtenant Structures for Dams (Spillways and Outlet Works) Design Standard

Chapter 3: General Spillway Design Considerations
Final: Phase 4

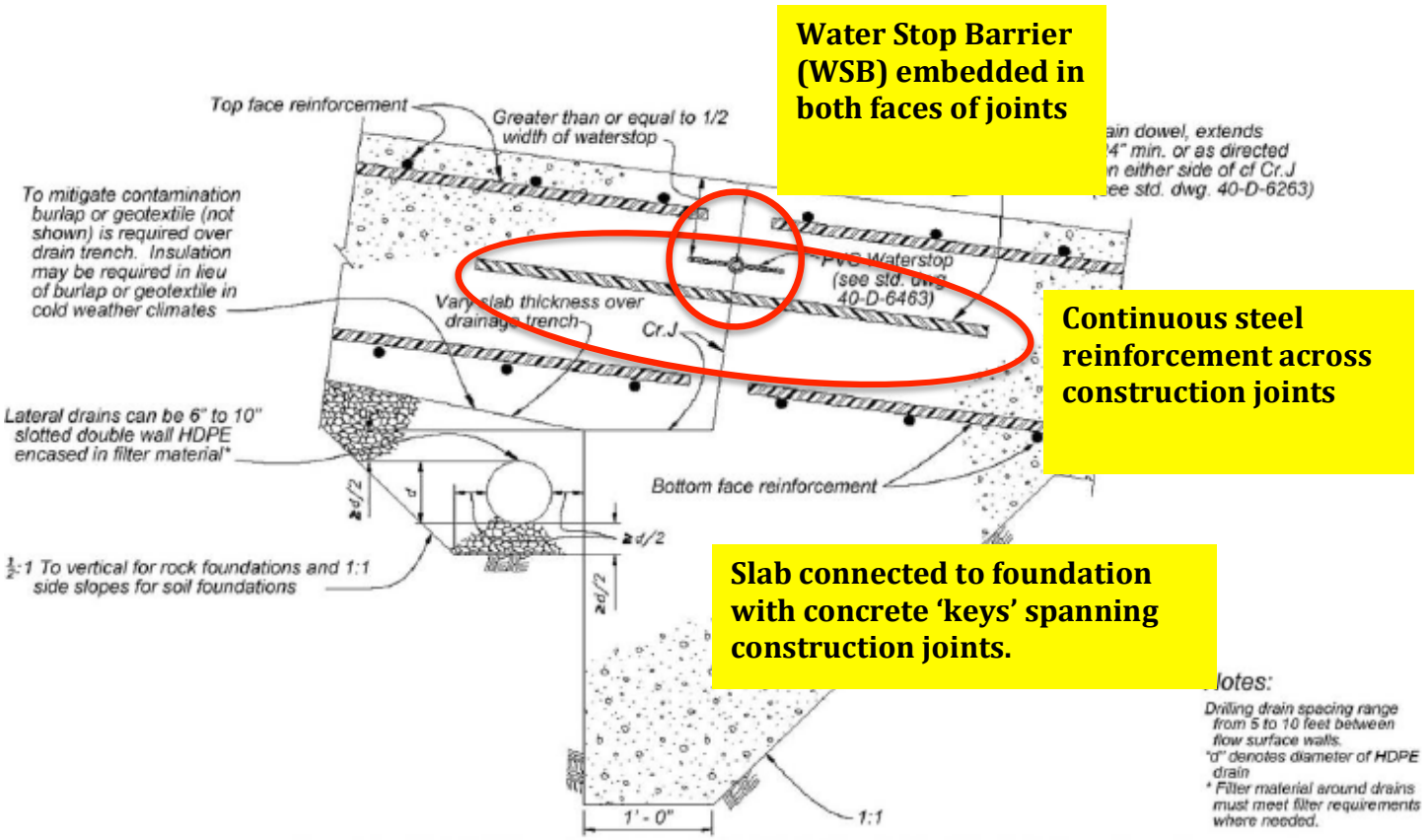
U.S. Department of the Interior
Bureau of Reclamation

August 2014

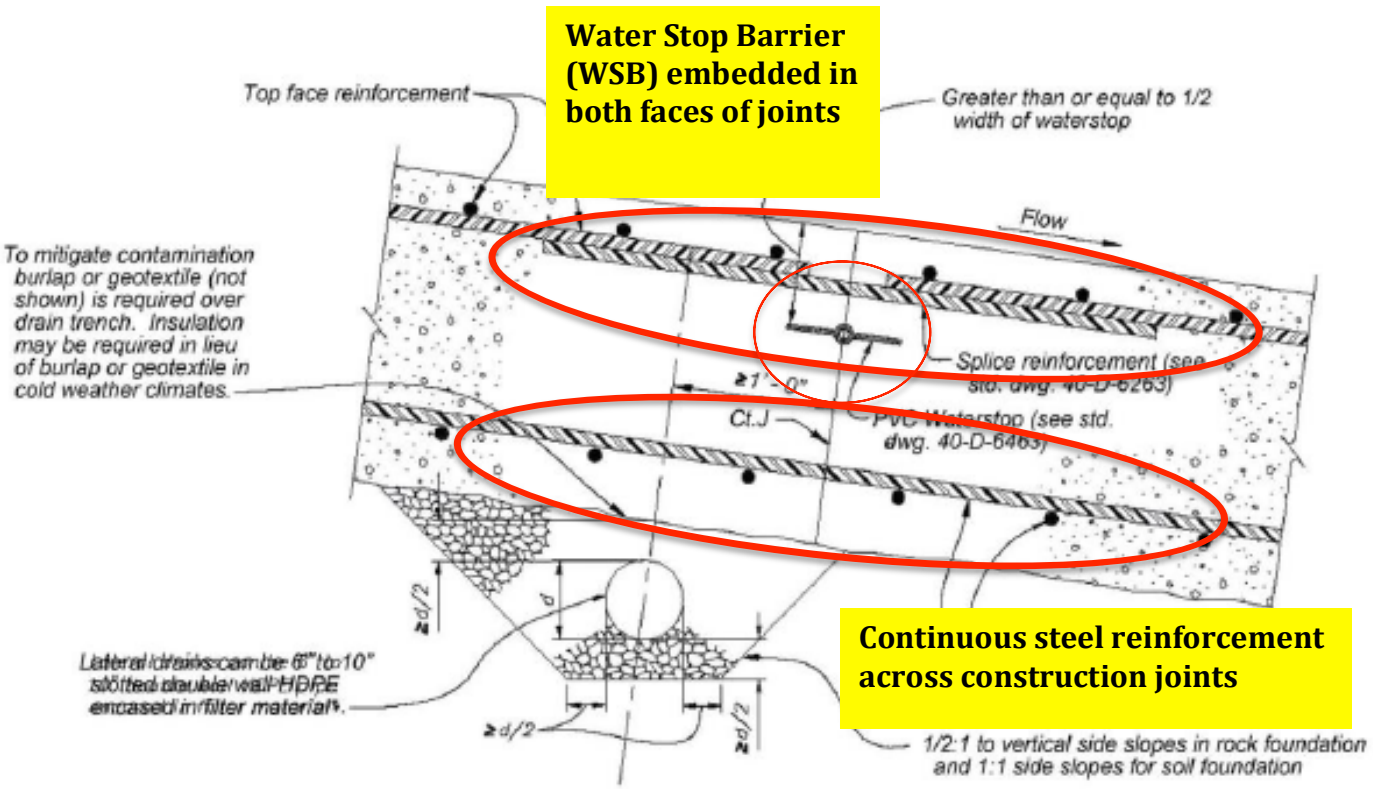


Water Stop Barrier (WSB) embedded in both faces of joints

Slab connected to foundation with concrete 'keys' spanning construction joints.



CASE 2B: ROCK OR SOIL FOUNDATION WITH FOUNDATION KEY – STEEP SLOPE – APPLICABLE FEATURE IS CONVEYANCE FEATURE (CHUTES)



CASE 1B: ROCK OR SOIL FOUNDATION WITHOUT FOUNDATION KEY – FLAT TO GRADUAL SLOPES – APPLICABLE FEATURE IS TERMINAL STRUCTURE (STILLING BASIN)